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C H E M I C A L E N G I N E E R I N G S E R I E S

CHEMICAL ENGINEERING FOR PRODUCTION SUPERVISION

BY

DAVID E. PIERCE

Chemical Engineer, Röhm and Haas Company, Philadelphia

FIRST EDITION
SIXTH IMPRESSION



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PREFACE

For the collegiate education of young men as chemical engineers, excellent textbooks have been available for nearly twenty years. For the nontechnical men of the chemical industry, however, for the foremen and supervisors in direct charge of operating chemical engineering equipment, there has not been a single understandable book to which they could turn for information about the basic principles upon which that equipment depends.

This need has been brought home to the author during the past year by his assignment to direct an Engineering Defense Training Course for nontechnical men in the organization of which he is a member. The notes used in the six months' course, as given to these men, have now been amplified to form the basis of this book. It is presented with the hope that it will meet the need of nontechnical operating men for a simple explanation of the equipment for which they are responsible.

In the effective use of this book, the problems are of the utmost importance. According to the author's belief, any training course using this book as a text should be so arranged that each student works, or at least attempts to solve, every problem in the book. Class discussions should clear up all baffling points as the work proceeds. Ability to make use of the data and the methods of calculation should be the primary aim, rather than recitation of the subject matter of the text. The point of view throughout the course should be that of the man who wants to analyze difficulties in operation, check efficiencies, and utilize his equipment to the best advantage.

The material for this book has been selected from textbooks, handbooks, technical journals, and manufacturers' bulletins. Such a method invites criticism. The author hopes that those who submit suggestions and criticism will assume the viewpoint of the operating man, so that future editions may make this book more useful to those for whom it is written.

The first chapter covers those principles of chemistry and physics which are needed for an understanding of the succeeding

chapters. Since many operating men have had no training in chemistry or have been out of touch with it for a number of years, as much as a fourth or a third of the entire course may be devoted to this chapter. The use of slide rules should be encouraged from the beginning of the study.

The second chapter, Transformation of Energy, is planned to acquaint the student with calculations involving energy in its various forms. The development of facility in using steam tables is to be emphasized at this stage of the study. The remaining chapters present the five unit operations of chemical engineering which are of major importance in most chemical plants. As previously suggested, the discussion of fundamental principles, rather than extended descriptions of many types of equipment, will be stressed.

In preparing the notes upon which the book is based, the author has been materially assisted by B. F. Feick, E. T. Sauer, and H. H. Tiedemann, all of the Röhm and Haas staff. Their help is gratefully acknowledged. Dr. M. C. Molstad of the University of Pennsylvania, under whose supervision the Defense Training Course was presented, has also given helpful suggestions and criticism. Among the many texts and reference books consulted in writing this book, "Principles of Chemical Engineering" by Walker, Lewis, McAdams, and Gilliland has been the chief source of information, and thanks are extended to the authors for their permission to use their material so extensively. Finally, the author wishes to express appreciation for the cooperation of the various manufacturers of engineering equipment for their courtesy in supplying illustrations.

DAVID E. PIERCE.

PHILADELPHIA, PA.,
January, 1942.

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CHEMICAL ENGINEERING FOR PRODUCTION SUPERVISION

CHAPTER I

GENERAL PRINCIPLES OF CHEMISTRY AND PHYSICS

Introduction.—Since chemical engineering may be defined as “that branch of applied science which has to do with the control of chemical reactions from the point of view of economy of materials, energy, and plant involved,” it is important to understand the meaning of the terms used in this definition. Thus, a *science* is a system of classified knowledge. An applied science involves the application of such classified knowledge to practical conditions.

The term *materials* includes what is known as matter, anything that has weight. Various properties of matter that are recognized in engineering include volume, density, state of aggregation, temperature, pressure, viscosity, and composition. One of the fundamental laws is that of Conservation of Matter, which states that matter can neither be created nor be destroyed.

Energy is the term applied to anything that causes change. It has been defined as “work and every other thing which can arise from work and be converted into work.” It is therefore measured by the changes produced in matter. There are various forms of energy, including mechanical, chemical, thermal (heat), electrical, and radiant energy. In considering the transformation of one form into another, the fundamental law is that of Conservation of Energy, which states that energy can be neither created nor destroyed.

The term *plant* covers the equipment in which the “control of chemical reactions” is made possible, including the containers for materials, the pipes and conduits by which matter and energy

are supplied and conveyed, and the instruments used in observing changes that take place.

CHEMICAL PRINCIPLES

Chemistry is defined as "the science which deals with the changes in composition and constitution which substances undergo, and with the alteration in properties which accompanies and gives evidence of those changes." It states that there are about 92 different kinds of matter, known as *elements* and existing as minute *atoms* which form relatively stable *molecules*. The molecules of pure substances are composed of atoms of the same kind; those containing atoms of different elements are called *compounds*.

Elements.—Each element is a separate kind of matter, differing fundamentally from every other kind and incapable of being converted into simpler substances, except in very rare cases. To avoid writing the name of each element involved in any operation, chemists have adopted symbols which stand for the names. Some of the most common of these, together with an estimate of the extent to which each one occurs, is given in Table I.

TABLE I.—THE MOST COMMON ELEMENTS*

Element	Percentage of our world	Symbol
Oxygen.....	49.98	O
Silicon.....	25.30	Si
Aluminum.....	7.26	Al
Iron.....	5.08	Fe
Calcium.....	3.51	Ca
Magnesium.....	2.50	Mg
Sodium.....	2.28	Na
Potassium.....	2.23	K
Hydrogen.....	0.94	H
Titanium.....	0.30	Ti
Carbon.....	0.21	C
Total.....	99.59	

* Alexander Smith, "General Chemistry for Colleges," D. Appleton-Century Company, Inc., New York, 1915.

Compounds.—When two or more elements combine to form a new substance having definite properties that are fundamentally different from those of the elements contained in it, this new sub-

stance is called a *compound*. It cannot be separated by physical means, such as grinding or vaporizing, into the constituent elements. An example is sodium chloride, a compound of sodium, a silvery metal, and chlorine, a greenish gas. The compound sodium chloride, is a white, crystalline solid, having properties entirely different from the elements of which it is formed. It is, in fact, common salt.

An important fact about compounds is expressed by the Law of Definite Proportions, which states that in any given compound, the proportion, by weight, of the constituents is always the same. Pure water, for example, always contains 11.2 per cent hydrogen and 88.8 per cent oxygen by weight. Pure cupric oxide, likewise, always contains 79.9 per cent copper and 20.1 per cent oxygen by weight.

TABLE II.—ATOMIC WEIGHTS OF SOME COMMON ELEMENTS*

Element	Symbol	Atomic weight	Element	Symbol	Atomic weight
Aluminum.....	Al	27.0	Nickel.....	Ni	58.7
Calcium.....	Ca	40.1	Nitrogen.....	N	14.0
Carbon.....	C	12.0	Oxygen.....	O	16.0
Chlorine.....	Cl	35.5	Phosphorus.....	P	31.0
Copper.....	Cu	63.6	Potassium.....	K	39.1
Gold.....	Au	197.2	Silicon.....	Si	28.1
Hydrogen.....	H	1.0	Silver.....	Ag	107.9
Iron.....	Fe	55.9	Sodium.....	Na	23.0
Lead.....	Pb	207.2	Sulphur.....	S	32.1
Magnesium.....	Mg	24.3	Tin.....	Sn	118.7
Mercury.....	Hg	200.6	Zinc.....	Zn	65.4

* These values have been rounded off to the nearest tenth, for convenience in calculation. Complete tables are available in textbooks and handbooks of chemistry.

Atoms.—These are the smallest particles of any element and cannot be further subdivided or broken down by *chemical* means. They are so small that no apparatus is available for directly measuring or weighing them. However, it is possible to compare large multiples of atoms with the same multiple of other atoms and thus establish the ratio of weights. It has been found convenient to adopt the weight of 1 atom of oxygen as 16, and to compare all other elements to this. By making such a comparison, atomic weights have been determined for all the elements. Some of those most commonly used are given in Table II.

Molecules.—Two or more atoms of the same kind, or of different kinds, unite to form a particle of matter called a *molecule*. Each molecule of a given substance is exactly like every other molecule of the same substance. As already mentioned, atoms of the same kind form molecules of pure substances; atoms of different kinds form molecules of compounds. Although a molecule is so minute as to be invisible to even the strongest microscope, it is assumed that one molecule can exist independently, whereas, in most cases, one atom cannot occur separately but only in combination with one or more other atoms to form a molecule.

The composition of a molecule is shown by writing a formula, made up of the symbols of the atoms contained in it. If there are two or more atoms of the same kind in a molecule, the number of such atoms is shown by a small figure placed after the symbol of the element. Thus, the molecule of oxygen is written as O_2 , showing that it contains two atoms of oxygen. In the same way, Cl_2 is the formula for the chlorine molecule, showing that each molecule contains two atoms of chlorine. Sodium chloride (common salt) has for its molecular formula $NaCl$, showing one atom each of sodium and of chlorine; the lack of any number after a symbol indicates that only one atom of that element is present in the molecule. The formula for sulphuric acid (H_2SO_4) shows that two atoms of hydrogen, one atom of sulphur, and four atoms of oxygen are found in every molecule of this compound.

The weight of a molecule must be the sum of all the atomic weights contained in it. Thus, the molecular weight of H_2SO_4 is calculated as,

$$\begin{array}{rcl} \text{Two atoms of hydrogen} & = 2 \times 1 & = 2.0 \\ \text{One atom of sulphur} & = & 32.1 \\ \text{Four atoms of oxygen} & = 4 \times 16 & = 64.0 \\ & & \hline \text{Total} & = & 98.1 \end{array}$$

In the same way, the molecular weight of sodium sulphide (Na_2S) is calculated:

$$\begin{array}{rcl} \text{Two atoms of sodium} & = 2 \times 23 & = 46.0 \\ \text{One atom of sulphur} & = & 32.1 \\ & & \hline \text{Total} & = & 78.1 \end{array}$$

The same method applies to the molecule of a pure substance. Oxygen (O_2) has a molecular weight of $2 \times 16 = 32$.

It is frequently convenient, in plant practice, to use as many pounds of a given substance as there are units in its molecular weight, calling such an amount one "pound mol." Accordingly, 1 lb. mol of oxygen is 32 lb., 1 lb. mol of sulphuric acid is 98.1 lb.

Valence.—Elements differ in their methods of combining with other elements. An atom of hydrogen, for example, can never combine with more than one other atom of any kind; oxygen can combine with two hydrogen atoms. It would seem, then, that hydrogen has only one "point of attachment," which chemists call *valence*. On this basis, the valence of oxygen is 2, as shown in the molecule of water (H_2O), where one atom of oxygen is attached to two atoms of hydrogen. From the formula for hydrochloric acid (HCl) it is seen that chlorine has a valence of 1, since it is attached to only one atom of hydrogen. The valence of any element, therefore, may be determined from the number of hydrogen atoms with which one of its atoms will combine.

If no known compound with hydrogen exists, the valence can be found from some other element that does combine with hydrogen. Sodium, for example, combines with chlorine as NaCl . Since chlorine has been shown to have a valence of 1 in HCl , it is evident that sodium has a valence of 1, since it combines in the ratio of 1:1 with chlorine.

Some elements have two or more different valences. Carbon, for example, may form carbon monoxide (CO) and carbon dioxide (CO_2). Since oxygen always has a valence of 2, it is evident that the carbon has a valence of 2 in CO and of 4 in CO_2 . Sulphur, likewise, is multivalent, having a valence of 4 in sulphur dioxide (SO_2) and of 6 in sulphur trioxide (SO_3).

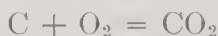
Radicals.—There are certain groups of atoms that act as though the whole group were an atom. Such groups are called *radicals* and are often enclosed in parentheses to show that they have a special relationship. For example, the group (NO_3), called the *nitrate radical*, is found in such compounds as sodium nitrate (NaNO_3), lead nitrate [$\text{Pb}(\text{NO}_3)_2$], and nitric acid (HNO_3). Each radical has a definite valence, the nitrate radical having a valence of 1. Other radicals are

Carbonate: (CO_3), as in CaCO_3

Sulphate: (SO_4), as in Na_2SO_4

Chlorate: (ClO_3), as in NaClO_3

Chemical Equations.—When atoms and molecules react to form new molecules, a chemical equation may be written. This is a statement in chemical symbols of the number and kind of molecules (or atoms) reacting with each other during a chemical change and of the products resulting from this reaction. Thus, the formation of carbon dioxide by burning carbon in oxygen is expressed as



This means that one atom of carbon reacts with one molecule of oxygen to form one molecule of carbon dioxide. In terms of the atomic weights, it also means that 12 parts by weight of carbon react with 32 parts by weight of oxygen to produce 44 parts by weight of CO_2 .

The equation, $\text{H}_2 + \text{S} = \text{H}_2\text{S}$, means that one molecule of hydrogen reacts with one atom of sulphur to form one molecule of hydrogen sulphide. That is, 2 parts by weight of hydrogen react with 32.1 parts by weight of sulphur to produce 34.1 parts by weight of H_2S .

The weight relationships expressed by such equations hold true for any uniform system of weights. Thus, the last equation is true whether the "parts by weight" are pounds, ounces, or tons. That is, 2 lb. of hydrogen react with 32.1 lb. of sulphur to yield 34.1 lb. of H_2S . In other words, it can be stated that the ratio of

$$\frac{\text{Atomic weights of hydrogen}}{\text{Atomic weights of sulphur}} = \frac{\text{real weight of hydrogen}}{\text{real weight of sulphur}}$$

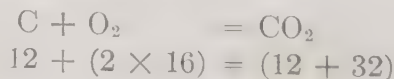
and

$$\frac{(\text{Atomic weights of sulphur} + \text{atomic weights of hydrogen})}{\text{Total atomic weights in hydrogen sulphide}} = \frac{\text{real weights of reactants}}{\text{real weights of products}}$$

The usefulness of such equations is illustrated by the following problem:

Illustration 1.—If 360 lb. of carbon is burned to form carbon dioxide, how many pounds of oxygen are used up and how many pounds of carbon dioxide are obtained?

The reaction is expressed as



Since atomic weights are to atomic weights as real weights are to real weights,

$$\frac{12 \text{ parts of carbon}}{32 \text{ parts of oxygen}} = \frac{360 \text{ lb. of carbon}}{x \text{ lb. of oxygen}}$$

$$x = \frac{32 \times 360}{12} = 960 \text{ lb. of oxygen used}$$

Also

$$\frac{12 \text{ parts of carbon}}{44 \text{ parts of carbon dioxide}} = \frac{360 \text{ lb. of carbon}}{y \text{ lb. of carbon dioxide}}$$

$$y = \frac{44 \times 360}{12} = 1,320 \text{ lb. of carbon dioxide produced}$$

States of Aggregation.—The form in which matter exists is called its *state of aggregation*. In the *solid* state, matter is rigid and tends to hold a definite shape, regardless of its position relative to the earth. *Crystalline* solids are those having definite, characteristic, geometric forms. Common salt, for example, crystallizes in cubes; quartz (rock crystal) has a hexagonal cross section with six-sided pyramids at the ends. *Amorphous* solids, on the other hand, have no definite form. Lampblack, one form of carbon, is amorphous, whereas diamond, another form of the same element, is crystalline.

In the *liquid state*, matter flows readily under the influence of gravity and assumes a level surface. *Pure liquids* consist of one element or one compound only, *e.g.*, mercury, a pure liquid metal and benzene, a pure liquid compound (C_6H_6). *Solutions*, as ordinarily defined, are liquids containing other liquids, solids, or gases in such finely divided form as to be perfectly homogeneous, clear, and transparent. *Suspensions* are liquids containing other finely divided liquids or solids completely dispersed but not dissolved. Such liquids are opaque or opalescent. If the suspended solids are so fine that they will not settle out and cannot be filtered out, the suspension is frequently called a *colloidal solution*.

The *gaseous state* of matter is that in which the matter flows freely in all directions. In this state, it will completely fill any container in which it is placed.

PROPERTIES OF MATTER

Weight.—One of the most important properties of matter is *weight*, the attraction of gravity for a given mass, expressed in

pounds, tons, etc. It is frequently convenient, however, to refer the weight of a given quantity of material to the weight of that quantity of water which would occupy the same space, measured under a definite set of conditions. This ratio is called the *specific gravity* of the material.

Volume.—Another property of matter is *volume*, the space occupied by any given quantity of matter. Measurements of volume are cubic inches, cubic feet, gallons, etc. The *specific volume* of a material is the number of cubic feet occupied by 1 lb. of the material under a specified set of conditions. *Density* is the weight per unit volume, usually pounds per cubic foot.

Temperature.—Thermal level, or temperature, is another important property of matter. When no heat flows from one body to another which is in good contact with it, the two bodies are said to be at the same temperature. *Thermometry*, the measurement of temperature, utilizes as “fixed points” the freezing point and the boiling point of pure water at “normal atmospheric pressure.”

On the *Fahrenheit* scale, the range of temperature between these two fixed points is divided into 180 degrees, the freezing point of water being arbitrarily taken as 32°F. and the boiling point, therefore, being 212°F. The lowest conceivable temperature, at which matter would contain no heat, is calculated to be 460° below 0°F. Measuring all temperatures above this *absolute zero* in degrees of the same magnitude as Fahrenheit gives the *Rankine* scale. Thus, this scale makes 0°F. equal 460°R. and the freezing point of water becomes $460^{\circ} + 32^{\circ} = 492^{\circ}\text{R.}$; the boiling point, 672°R.

Another temperature scale, used in all chemical laboratories and in some plants, is the *centigrade* scale. The same fixed points are used as for Fahrenheit, but the difference between them is divided into 100 equal degrees, the freezing point of water being taken as 0°C. Thus the boiling point is 100°C. Using degrees of this magnitude, the absolute zero becomes -273°C. As before, an absolute scale may be used, measuring up from absolute zero. This is the *Kelvin* scale. The freezing point of water, on this scale, is 273°K. and the boiling point is 373°K.

Pressure.—Pressure is that property of matter which represents the force per unit area exerted against other matter. The units of measurement in common use include atmospheres,

pounds per square inch or per square foot, and equivalent heights of material which exert definite pressures, such as inches of mercury or feet of water.

Heat Content.—Among various other properties of matter, heat content is of immediate importance. As noted previously, heat is one form of energy. It is measured by its effect, one *British thermal unit*, or B.t.u., being the quantity of heat required to raise the temperature of one pound of water through one degree Fahrenheit. For any other material, the ratio of the heat required to raise one pound of it through a given temperature range to the heat required to raise one pound of water through the same number of degrees is called the *specific heat* of that material. In other words, the specific heat of any material (solid, liquid, or gaseous) is expressed numerically as the number of B.t.u. required to raise the temperature of one pound of it through one degree Fahrenheit.

FACTORS

For convenience in solving problems involving the various properties of matter, the following factors may be used:

Volume :

$$\begin{aligned} 1 \text{ cu. ft.} &= 1,728 \text{ cu. in.} \\ &= 7.48 \text{ gal.} \end{aligned}$$

Temperature :

$$\begin{aligned} ^\circ\text{F.} &= (1.8 \times ^\circ\text{C.}) + 32^\circ \\ ^\circ\text{C.} &= \frac{^\circ\text{F.} - 32^\circ}{1.8} \\ 1^\circ\text{C.} &= 1.8^\circ\text{F.} \\ 1^\circ\text{F.} &= \frac{5}{9}^\circ\text{C.} \\ ^\circ\text{R.} &= ^\circ\text{F.} + 460^\circ \end{aligned}$$

Pressure :

$$\begin{aligned} 1 \text{ atmosphere} &= 14.7 \text{ lb. per sq. in.} \\ &= 29.9 \text{ in. of mercury} \\ &= 33.9 \text{ ft. of water at } 60^\circ\text{F.} \end{aligned}$$

Weight :

$$\begin{aligned} 1 \text{ ton} &= 2,000 \text{ lb.} \\ 1 \text{ gal. of water} &= 8.33 \text{ lb. at } 60^\circ\text{F.} \\ 1 \text{ cu. ft. of water} &= 62.4 \text{ lb. at } 60^\circ\text{F.} \end{aligned}$$

Standard Conditions :

Temperature of $32^{\circ}\text{F.} = 0^{\circ}\text{C.}$

Pressure of 1 atmosphere = 14.7 lb. per sq. in. absolute

CHANGES OF STATE OF AGGREGATION

When matter changes from one state of aggregation to another, *e.g.*, solid to liquid or gaseous to liquid, there are always changes in properties. These always involve energy as well as matter and are of direct importance in chemical plant operations.

Vaporization.—The change from the liquid to the gaseous state is called *vaporization*, the formation of a vapor. In order to cause this change, heat must be supplied, the amount of heat (B.t.u.) required to convert one pound of a liquid into one pound of vapor being known as the *latent heat of vaporization*. It is always the same number of B.t.u. for any given substance at any specified temperature but is different for every different substance. Thus, under atmospheric pressure, 1 lb. of water at 212°F. requires 970 B.t.u. to convert it into 1 lb. of water vapor (steam) at 212° ; 1 lb. of benzene (C_6H_6) at 176°F. requires 168 B.t.u. for complete vaporization; and 1 lb. of methanol (CH_3OH) at 149°F. uses 471 B.t.u. in changing from the liquid to the gaseous state. Since the vapor produced is at the same temperature as the liquid from which it has been converted in each case, the heat of vaporization is said to be “latent” because its effect is not shown by temperature rise.

Whenever a liquid has any space above it, *i.e.*, when it does not completely fill the container, some of it always vaporizes and continues to do so until its vapor reaches a certain definite pressure against the surface of the liquid and against the walls of the vessel and the atmosphere above it (in case the vessel is vented to the atmosphere). The pressure at which this vaporization stops is called the *vapor pressure* of the liquid at the existing temperature. - It varies with the temperature and is different for each different liquid. The presence of any other gas in the space above the liquid does not change the effect at all, so long as the other gas is insoluble in the liquid. That is, water vapor over pure water at 80°F. exerts a pressure of 0.51 lb. per square inch against the surrounding surfaces, whether it is the only gaseous material present or whether the space also contains air at a pressure of 100 lb. or of 50 lb. per square inch. This fact, that the vapor pressure of a liquid depends only upon its temperature,

and not at all upon other insoluble gases that may be present, is of extreme importance in many chemical engineering problems to be considered later.

The effect of temperature upon the vapor pressure of a liquid is very marked, higher temperatures causing higher vapor pressures. Table III shows the vapor pressure of water at several temperatures.

TABLE III.—VAPOR PRESSURE OF WATER (ABBREVIATED)

Temperature, °F.	Vapor Pressure, lb. per sq. in.
80	0.51
118	1.60
164	5.21
190	9.34
212	14.7

Whenever the vapor pressure of a liquid equals the total pressure of the atmosphere to which the vessel is vented, any further vaporization will cause a slight excess pressure and will push back the atmosphere, thus allowing some of the vapor to escape. This type of vaporization is called *boiling* and will continue as long as the latent heat is supplied (*e.g.*, by a heating coil) and as long as the resulting vapor has a free exit. The temperature at which this action takes place is called the *boiling point* of the liquid at the existing pressure. If the pressure in the space to which the vapor escapes is reduced by means of a pump, then boiling will take place at a correspondingly lower vapor pressure and therefore at a lower temperature. Evidently, each temperature at which water has the vapor pressure shown in Table III is also the boiling point of water when the pressure above it is held at the indicated amount.

Condensation.—The change of state from a vapor to a liquid, the reverse of vaporization, is called *condensation*. It requires the removal of an amount of heat per pound exactly equal to that which must be supplied to vaporize one pound of the material at that temperature. In other words, the *latent heat of condensation* is exactly equal to the latent heat of vaporization. Condensation occurs at that temperature at which the vapor pressure of the gas equals that of the liquid. Thus, if water vapor is at a pressure of 0.51 lb. per square inch and a temperature of 100°F., it remains as a gas (also called a *superheated vapor*). However, if the temperature is lowered until it reaches 80°F., keeping the pressure at 0.51 lb. per square inch, the vapor is said to be

saturated. Any further cooling will not lower the temperature but will cause condensation, which will continue at 80°F. as long as the pressure of the vapor is maintained at 0.51 lb. per square inch and heat is removed.

Fusion.—Conversion of a solid into a liquid is called *fusion*. As in other changes of state, a very definite quantity of heat is involved. As in the case of vaporization, heat must be added, the number of B.t.u. required to melt one pound of any substance being called the *latent heat of fusion* of that substance. Since fusion occurs at a very definite temperature for each pure material, this *melting point* is a valuable means of identifying unknown substances. In this change of state, as in those already considered, the temperature of the material remains constant until all of the change has occurred. In Table IV, are given the melting points and latent heats of fusion of several substances.

TABLE IV.—MELTING POINTS AND LATENT HEATS

Substance	Melting point, °F.	Latent heat of fusion, B.t.u. per lb.
Ice (H ₂ O).....	32	144
Benzene (C ₆ H ₆).....	42	55
Acetone (CH ₃ COCH ₃).....	— 138	42.2
Mercury.....	— 38	5.1
Sulphur.....	235	16.7

Solidification.—The reverse of fusion is *solidification*, the change from a liquid to a solid state. The temperature at which this occurs, the *freezing point*, is the same as the melting point for each pure material. Likewise, the latent heat that must be removed to change one pound of the given liquid to a solid at the same temperature, is the same number of B.t.u. that must be added to melt that pound of solid.

GAS LAWS

So many chemical engineering operations involve the handling of gases that special attention must be given to the properties of matter in the gaseous state. Certain relationships have been discovered which hold so well for certain gases at moderate pressures and which are so useful that they are known as the “gas laws.” Although these laws apply exactly only to a nonexistent

"perfect gas," they are sufficiently accurate for engineering purposes for most actual gases, provided these gases are at moderate pressures and are considerably superheated (*i.e.*, not close to condensation). They may even be applied to vapors near the condensing point if no better data are available, it being understood that an error is introduced by using them under these conditions.

Boyle's Law.—This law states that *at any given temperature, the volume of a given weight of gas, multiplied by the pressure of that gas, is a constant.* Expressed as a formula,

$$pv = \text{constant}$$

Thus, if 10 lb. of a certain gas has a volume of 125 cu. ft. at 70°F. when the pressure is 2,000 lb. per square foot,

$$pv = 2,000 \times 125 = 250,000 \text{ (the constant for this case)}$$

If the pressure is changed to 1,000 lb. per square foot, keeping the temperature at 70°F., the volume of the 10 lb. of gas can then be obtained by substitution:

$$\begin{aligned} 1,000v &= 250,000 \\ v &= 250 \text{ cu. ft.} \end{aligned}$$

If the pressure is now changed so that the volume is 500 cu. ft., keeping the temperature at 70°F., the new pressure can be calculated:

$$\begin{aligned} 500p &= 250,000 \\ p &= 500 \text{ lb. per sq. ft.} \end{aligned}$$

Another way of stating this law is to say that at any fixed temperature, where the pressure is p_1 and the volume of a given weight of gas is v_1 , the pressure may be changed to p_2 and the resulting volume will be v_2 , the values being related as shown by the formula

$$p_1v_1 = p_2v_2 = \text{constant}$$

Obviously, we may also write,

$$\frac{p_1}{p_2} = \frac{v_2}{v_1}$$

Avogadro's Law.—This law states that *at any specified temperature and pressure, a given volume of one gas will contain the same number of molecules of that gas as are contained in the same volume of any other gas at the same temperature and pressure.* This is held

to be true whether we have one single kind of gas or a mixture. Thus, 100 cu. ft. of oxygen at 50°F. and at 1 atmosphere pressure contains the same number of molecules as 100 cu. ft. of nitrogen or as 100 cu. ft. of air, at the same temperature and pressure.

The same law holds true for pound molecules (pound mols) of any gas. That is, if there are 10 lb. mols of oxygen (320 lb.) in a certain vessel, the same vessel, when filled with hydrogen or with nitrogen at the same temperature and pressure, will be found to hold 10 lb. mols of hydrogen (20 lb.) or 10 lb. mols of nitrogen (280 lb.).

Pound Molecular Volume.—Reasoning from Avogadro's law and its application to pound mols, it is evident that one pound mol of one kind of gas must occupy the same volume as one pound mol of any other kind of gas, providing both are at the same temperature and pressure. By adopting as standard conditions a pressure of 1 atmosphere (14.7 lb. per square inch) and a temperature of 32°F., it has been found that one pound mol of any "perfect" gas occupies 359 cu. ft. Actual gases, as mentioned previously, are generally close enough to "perfect gases" for engineering calculations so that the statement may be made that *one pound mol of any gas has a volume of 359 cu. ft. at standard conditions of one atmosphere pressure and a temperature of 32°F.* The volume of a pound mol at any other conditions may then be calculated from Boyle's law or those that follow.

Charles's Law.—*For any specified weight of a given gas, the product of its volume by the existing pressure is proportional to the absolute temperature of the gas in degrees Rankine.* This law may be stated as a formula:

$$pv = KT$$

The constant K does not change in value, so long as the same number of pounds of the same gas are under consideration and so long as the values of p and of v are expressed in the same units. It is different, however, for different gases and for different quantities of the same gas.

To illustrate the use of the law, consider the following problem:

Illustration 2.—At 32°F. and atmospheric pressure, 29 lb. of air occupies a volume of 359 cu. ft. What is the volume at 150°F. and at a pressure of 2 atmospheres? The value of the constant K is found by substituting for p its value in atmospheres ($=1$),

for v the given volume of 359 cu. ft., and for T the temperature in degrees Rankine ($=460^{\circ} + 32^{\circ} = 492^{\circ}\text{R.}$).

$$pv = KT$$

Then

$$1 \times 359 = K \times 492$$

$$K = \frac{359}{492} = 0.73$$

Using this value for K , the formula may now be set up to find the unknown volume (v_2), the new pressure (p_2) being 2 atmospheres and the new temperature (T_2) being $460^{\circ} + 150^{\circ} = 610^{\circ}\text{R.}$ Then

$$p_2 v_2 = KT$$

$$2v_2 = 0.73 \times 610$$

$$v_2 = \frac{0.73 \times 610}{2} = 223 \text{ cu. ft.}$$

Dalton's Law of Partial Pressures.—This law states that *in a mixture of gases, each gas exerts the same pressure as it would exert if it were present alone in the volume occupied by the mixture.* In other words, the pressure of each gas in a vessel depends entirely upon the number of mols of that gas and its temperature, and is entirely independent of the pressure exerted by each of the other gases in the mixture. In a mixture of gases, therefore, the total pressure on the walls of the container must be the sum of the individual pressures (called the "partial pressures") of all the gases present. Representing the total pressure as P and the individual or partial pressures as p_1, p_2 , etc., Dalton's law may be stated as a formula:

$$P = p_1 + p_2 + p_3$$

Evidently, if we add a quantity of another gas that would have a pressure of p_4 if it were placed in the vessel alone at the existing temperature, the new total pressure

$$P_y = P + p_4 = p_1 + p_2 + p_3 + p_4$$

As an example, consider a 10 cu. ft. vessel at 70°F. , containing oxygen at a pressure of 5 lb. per square inch and another 10 cu. ft. container in which there is hydrogen at 15 lb. per square inch pressure at 70°F. If the hydrogen is all pumped into the original vessel, mixing with the oxygen, and the temperature is still held

at 70°, the pressure of the oxygen (now called "partial pressure") will still be 5 lb. per square inch and that of the hydrogen will still be 15 lb. per square inch, just as though each gas were in its own container. The total pressure that would be indicated by an absolute pressure gage, therefore, would be $5 + 15 = 20$ lb. per square inch.

In discussing pound molecular volume, it was noted that one pound mol of any perfect gas occupies 359 cu. ft. at 32°F. and atmospheric pressure. Another way of stating the same fact would be to say that one pound mol of any perfect gas at 32°F., occupying a volume of 359 cu. ft., will exert a pressure of 14.7 lb. per square inch. That is, it is evident that one pound mol of any perfect gas exerts the same pressure as one mol of any other perfect gas, if the temperature and volume are the same in each case. From this conclusion, it is then apparent that the total pressure in a vessel is simply the product of the number of mols present multiplied by the pressure that one mol would exert in the same vessel at the existing temperature. This is true, regardless of the number of different kinds of gas. Thus, if 1 mol of oxygen exerts a pressure of 15 lb. per square inch when present alone in a certain vessel at 100°F., the total pressure exerted on the walls of the same container at 100°F. by 99 mols of nitrogen and 10 mols of oxygen would be $(99 + 10) \times 15 = 109 \times 15 = 1,630$ lb. per square inch.

From the above reasoning, it can be seen that the portion of the total pressure in a vessel exerted by one mol of gas is determined by the proportion of that mol to the total number of mols present. Thus, if there are 10 lb. mols of mixed gas in a container at a total pressure of 200 lb. per square inch, *each* mol exerts 10 per cent of 200 lb., or 20 lb. per square inch. If 2 of the 10 mols are oxygen and the remaining 8 are nitrogen, the oxygen mols are 20 per cent of the total and, therefore, the partial pressure of oxygen in the vessel is 20 per cent of 200 lb., or 40 lb. per square inch. This ratio of the mols of oxygen to the total number of mols of gas present is called the *mol fraction* of the oxygen in the mixture. We may then state that *the partial pressure exerted by any gas in a mixture is equal to its mol fraction multiplied by the total pressure.*

Representing the partial pressure of each of three gases in a mixture by p_a , p_b , and p_c , the total pressure by P , and the mol fractions as x_a , x_b , and x_c :

$$P = p_a + p_b + p_c$$

$$x_a = \frac{\text{mols of gas } a}{\text{mols of } a + \text{mols of } b + \text{mols of } c}$$

$$x_b = \frac{\text{mols of } b}{\text{total mols}}$$

$$x_c = \frac{\text{mols of } c}{\text{total mols}}$$

$$p_a = x_a P \quad \therefore x_a = \frac{p_a}{P}$$

$$p_b = x_b P \quad \therefore x_b = \frac{p_b}{P}$$

$$p_c = x_c P \quad \therefore x_c = \frac{p_c}{P}$$

It is now evident that the mol fraction of any gas in a mixture is numerically equal to the fraction of the total pressure that is exerted by this gas.

The use of these relationships is shown by the following examples:

Illustration 3.—In a mixture of chlorine, nitrogen, and carbon dioxide, there are 5 mols of Cl_2 , 10 of N_2 , and 35 of CO_2 and the total pressure is 500 mm. of mercury. What is the mol fraction of the Cl_2 and what is its partial pressure?

$$x = \frac{\text{mols } \text{Cl}_2}{\text{total mols}} = \frac{5}{5 + 10 + 35} = \frac{5}{50} = 0.10 \text{ (mol fraction)}$$

$$p = Px = 500 \times 0.10 = 50 \text{ mm. (partial pressure)}$$

Illustration 4.—The partial pressure of water vapor in an air mixture at atmospheric pressure is 0.147 lb. per square inch. What is the mol fraction of the water vapor?

$$x = \frac{p}{P} = \frac{0.147}{14.7} = 0.01$$

That is, in every 100 mols of the "wet air," there are 99 mols of dry air and 1 mol of water.

The Law of Perfect Gases.—Practically all the various laws discussed so far may be combined in the very useful statement known as the Law of Perfect Gases. This states that *the product of the pressure times the volume equals the product of the number of*

mols of gas present, the absolute temperature, and a constant known as the gas constant, R . As a formula:

$$pv = NRT$$

In using this equation, the gas constant R is 1,543 when the variables are expressed in the following units:

p = pressure, in pounds per square foot (absolute).

v = volume, in cubic feet.

N = number of pound mols.

T = absolute temperature, in degrees Rankine.

To illustrate the application of this law:

Illustration 5.—At what pressure would 88 lb. of carbon dioxide gas occupy a volume of 100 cu. ft. when the temperature is 10°F.? Note that $N = \frac{88}{44} = 2$ mols, $v = 100$ cu. ft., and

$$T = 460^\circ + 10^\circ = 470^\circ \text{R.}$$

Then

$$pv = NRT, \quad p = \frac{NRT}{v}$$

$$\therefore p = \frac{2 \times 1,543 \times 470}{100} = 14,500 \text{ lb. per sq. ft.}$$

Since pressure is generally stated as pounds per square inch, this result may be converted to that basis by dividing by 144, the number of square inches in a square foot. Then

$$\frac{14,500}{144} = 101 \text{ lb. per sq. in. absolute}$$

To get gage pressure, subtract 14.7 lb. per square inch,

$$101 - 14.7 = 86.3 \text{ lb. per sq. in.}$$

PROPERTIES OF SOLUTIONS

Solutions differ from the pure liquids from which they are made in many important respects. Thus, dissolving a material in a liquid changes the density, specific heat, vapor pressure, viscosity, and other characteristics. It is therefore important to consider some of these effects.

Degrees of Solubility.—Although certain substances are completely soluble in certain liquids (*e.g.*, alcohol in water), most materials are definitely limited in the amount that can be dis-

solved in a specified amount of the liquid. Also, this degree of solubility varies with temperature, usually (but not always) being greater at the higher temperatures. When a solution contains the maximum amount of a given substance that it can hold in the presence of an excess of the undissolved solid, it is said to be "saturated" at that temperature.

Concentration.—The *concentration* of a solution (*i.e.*, the amount of solid dissolved in it) may be expressed in several ways: the pounds of solid per 100 lb. of solution (*i.e.*, weight per cent), the pounds of solid per 100 lb. of pure solvent, or the mols of solid per 100 mols of solution (*i.e.*, mol per cent). In making calculations, therefore, it is necessary to observe carefully the form in which concentrations are given.

Table V expresses the "solubility" (*i.e.*, the concentration) of certain saturated solutions as pounds of the given solid per 100 lb. of water at 18°C. (64.4°F.).

In Table VI, the effect of temperature on degree of solubility is shown for saturated solutions of sulphur in carbon disulphide (CS_2), the concentrations being expressed as pounds of sulphur per 100 lb. of solution.

TABLE V.—SOLUBILITIES AT 18°C.

Solid	Lb. per 100 lb. of water	Solid	Lb. per 100 lb. of water
NaCl.....	35.9	CaCl_2	73.2
NaNO_3	84.0	CaSO_4	0.20
NaOH.....	116.0	CaCO_3	0.0013
Na_2SO_4	16.8	$\text{Ca}(\text{OH})_2$	0.17
Na_2CO_3	19.4	ZnCl_2	204.0

TABLE VI.—SOLUBILITY OF S IN CS_2

Temperature, °F.	Lb. per 100 lb. of Solution
50	23.0
104	50.0
122	59.0

Heat of Solution.—When one substance is dissolved in another, there is always an *evolution* or an *absorption* of heat. That is, the solution rises in temperature in some cases and falls in others. A good example of heat evolution may be observed in the solution of sulphuric acid in water (see Prob. 101). The reverse effect is

illustrated by the absorption of 6980 B.t.u. when 1 lb. mol of ammonium chloride (53.5 lb.) is dissolved in a large amount of water. In the latter case, the solution is found to have dropped in temperature by the amount necessary to supply the heat indicated.

Boiling-point Raising.—The effect of the presence of a dissolved solid on the vapor pressure of the liquid solvent is of considerable importance in many chemical engineering problems. This effect is always to decrease the vapor pressure, so that at any given pressure the solution must be raised to a higher temperature than the pure liquid before boiling takes place. The number of degrees rise, thus required, is called the *boiling-point raising* (B.P.R.) for the given solution and is greater for greater concentrations. In some cases, the number of degrees rise is the same definite amount for each mol of dissolved material in a specified amount of solvent. Thus, 1 lb. mol of sugar, dissolved in 1,000 lb. of water, raises the boiling point 0.93°F. , and 0.5 lb. mol in 1,000 lb. of water causes half this rise. This same B.P.R. is found to apply to a pound mol of various other materials. However, certain substances (such as salts) cause greater effects on the boiling point than would be calculated from their molal concentrations.

Table VII shows the very marked effect of concentration on the boiling point for solutions of caustic soda in water at atmospheric pressure, the concentrations being expressed as per cent NaOH.

Freezing-point Lowering.—The freezing point of a solution is always lower than the freezing point of the pure solvent, the effect being greater with greater concentration of dissolved material. As in the case of B.P.R., the number of degrees lowering is sometimes directly proportional to the number of pound mols of dissolved material per specified weight of solvent. Thus, the following substances each lower the freezing point of water about 3.4°F. when one pound mol is dissolved in 1,000 lb. of water:

	Molecular Weight
Sugar ($\text{C}_{12}\text{H}_{22}\text{O}_{11}$).....	342
Ethanol ($\text{C}_2\text{H}_5\text{OH}$).....	46
Methyl acetate ($\text{C}_3\text{H}_6\text{O}_2$).....	74

For certain materials, especially salts, the effect is considerably greater than the value noted above. For example, 1 lb. mol. of sodium chloride (58.5 lb.) dissolved in 2,000 lb. of water lowers the

TABLE VII.—BOILING POINTS OF CAUSTIC SODA SOLUTION

Per Cent NaOH	Boiling Point, °F.
12	219
20	226
33	248
40	263
50	289

freezing point 3.1°F . This lowering is therefore almost twice as great, per 1,000 lb. of water, as that caused by the substances mentioned above.

When freezing of a solution does take place, the crystals formed are usually those of the pure solvent. This explains the statement that water is purified by freezing, since the impurities tend to remain in any of the water that has not frozen. It also explains how fruit juices may be concentrated by partial freezing and filtering out of ice crystals.

To illustrate the application of the principles relating to properties of solutions, the following problems are given:

Illustration 6.—When 1 lb. of caustic soda (NaOH) is dissolved to form a 25 per cent solution, 452 B.t.u. are evolved. The specific heat of the 25 per cent solution is 0.84. Calculate: the number of pounds of solution, heat evolved per pound of solution, and the rise in temperature of the solution, neglecting radiation loss.

Since 1 lb. of NaOH is 25 per cent of the solution, let x equal the total pounds of solution. Then

$$1 = 0.25x$$

$$x = 4 \text{ lb. of solution}$$

The total heat evolved is 452 B.t.u., which is carried by the whole solution.

$$\frac{452}{4} = 113 \text{ B.t.u. evolved per lb. of solution}$$

Since 1 lb. of solution requires 0.84 B.t.u. to raise its temperature 1°F ., the heat rise would be

$$\frac{113}{0.84} = 135^{\circ}\text{F}.$$

Illustration 7.—If 100 lb. of caustic soda (100 per cent NaOH) is dissolved to form a 25 per cent solution by adding it to a mixture of water and ice at 32°F ., how many pounds of ice will be required

so that the final temperature will be 100°F.? Assume the solid NaOH to be at 32°F. when added.

From the preceding problem, each pound of NaOH produces 4 lb. of 25 per cent solution, so that the final solution will be $100 \times 4 = 400$ lb., requiring 300 lb. of water (and ice) plus the 100 lb. of solid NaOH.

The total heat evolved is $100 \times 452 = 45,200$ B.t.u.

The heat absorbed in warming the total solution (after ice is melted) from 32 to 100°F. is

$$400 \times 0.84(100^\circ - 32^\circ) = 400 \times 0.84 \times 68 = 22,800 \text{ B.t.u.}$$

The heat to be absorbed by melting ice is

$$45,200 - 22,800 = 22,400 \text{ B.t.u.}$$

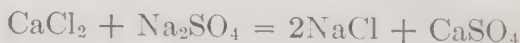
The latent heat of fusion of ice is 144 B.t.u. per pound, so that

$$\frac{22,400}{144} = 156 \text{ lb. of ice}$$

$$\therefore 300 - 156 = 144 \text{ lb. of water}$$

$\therefore$ Dissolve in a mixture of 144 lb. of water and 156 lb. of ice.

Illustration 8.—A thousand pounds of water is saturated with calcium chloride (CaCl_2) at 18°C. Enough sodium sulphate (Na_2SO_4) is added to complete the following reaction:



The precipitate is filtered off, making a wet cake containing 75 per cent CaSO_4 . What is the weight of the cake? What weight of CaSO_4 remains in solution?

According to Table V, 73.2 lb. of CaCl_2 is dissolved in 1,000 lb. of water. The equation shows that 1 mol of CaSO_4 is formed per mol of CaCl_2 . The molecular weight of CaSO_4 is calculated as $40.1 + 32.1 + 4 \times 16 = 136.2$ and that of CaCl_2 is

$$40.1 + 2 \times 35.5 = 111.1 \text{ (rounded off to 111).}$$

Then

$$\frac{136}{111} = 1.23 \text{ lb. of } \text{CaSO}_4 \text{ formed per lb. of } \text{CaCl}_2$$

$$73.2 \times 1.23 = 90.0 \text{ lb. of } \text{CaSO}_4 \text{ formed from the solution}$$

Since 1,000 lb. of water is saturated at this temperature by 2.0 lb.

of CaSO_4 , the precipitate will contain

$$90.0 - 0.20 = 88.0 \text{ lb. of } \text{CaSO}_4 \text{ (solid)}$$

In the filter cake, this is 75 per cent of the weight.

Let x = weight of wet cake,

$$0.75x = 88.0 \text{ lb.}$$

$$x = 117.3 \text{ lb. of wet cake}$$

As noted above, 2.0 lb. of CaSO_4 remains dissolved in the water. 125

Illustration 9.—A tank 4 ft. in diameter is filled to a depth of 61.5 in. with water. When 1,000 lb. of a certain salt is added to the tank, the freezing point of the resultant solution is found to be 4°F . If the freezing point lowering of the salt per mol is assumed to be twice that of sodium chloride (NaCl), what is the molecular weight of the salt?

The volume of the water in the tank is calculated as $0.785D^2h$, where D = diameter in feet and h = height of water in feet.

$$\therefore \text{Volume} = 0.785 \times (4)^2 \times \frac{61.5}{12} = 64.2 \text{ cu. ft.}$$

Taking the density of water as 62.4 lb. per cubic feet,

$$\text{Weight} = 64.2 \times 62.4 = 4,000 \text{ lb. of water}$$

Then, the concentration of salt is $1,000 \times (1,000/4,000) = 250 \text{ lb. per } 1,000 \text{ lb. of water}$. The freezing point lowering is $32^\circ - 4^\circ = 28^\circ\text{F}$. Since the lowering was assumed to be twice as great per mol as for NaCl , 0.5 mol of which per 1,000 lb. of water depressed the freezing point 3.1°F ., equivalent to 6.2° per mol, this salt would be expected to cause a lowering of $2 \times 6.2^\circ = 12.4^\circ$ per mol in 1,000 lb. of water.

$$\therefore \frac{28^\circ}{12.4^\circ} = 2.25, \text{ the number of mols per } 1,000 \text{ lb.}$$

Then

$$\frac{250}{2.25} = 111 \text{ lb., the weight per mol of salt}$$

It may be observed that this is the molecular weight of calcium chloride (CaCl_2).

Problems

1. A certain compound, when analyzed, is found to contain 79.9 per cent copper and 20.1 per cent oxygen. How many atoms of copper are there per atom of oxygen?

2. If 636 lb. of copper is to be converted into the above compound (cupric oxide), how many pounds of oxygen will be required?

3. If 954 lb. of copper is completely converted to cupric oxide (CuO), using 300 lb. of oxygen, how much excess oxygen was present in the reaction kettle? What percentage of excess is this?

4. Taking the molecular formula of water as H_2O , how many pounds of each element are there in 99 lb. of water?

5. In sulphur dioxide (SO_2), what is the percentage of sulphur by weight?

6. In 40 lb. of sulphur trioxide, we find approximately 16 lb. of sulphur and 24 lb. of oxygen. How many atoms of oxygen are there per atom of sulphur?

7. How many pounds of sulphur would be required to produce 1 ton (2,000 lb.) of sulphur dioxide?

8. How much sulphur trioxide (SO_3) would this amount of sulphur produce?

9. If 100 lb. of hydrogen is burned completely in air, how many pounds of water are produced?

10. If the oxygen to make the cupric oxide in Prob. 2 comes from water, how many pounds of water will be used? How much hydrogen would be set free?

11. Using the atomic weights given in the text, calculate the molecular weights of the following compounds:

Methane (CH_4)

Sodium hydroxide (NaOH)

Sulphuric acid (H_2SO_4)

Ammonia (NH_3)

Ammonium hydroxide (NH_4OH)

Ferric chloride (FeCl_3)

Formaldehyde (HCHO)

Phenol ($\text{C}_6\text{H}_5\text{OH}$)

Nitric acid (HNO_3)

Carbon disulphide (CS_2)

12. How many pound mols of each compound are there in each of the following quantities?

44 lb. of carbon dioxide (CO_2)

64 lb. of methane (CH_4)

112 lb. of carbon monoxide (CO)

2,046 lb. of hydrogen sulphide (H_2S)

130 lb. of formaldehyde (HCHO)

100 lb. of sodium hydroxide (NaOH)

72 lb. of water (H_2O)

188 lb. of phenol ($\text{C}_6\text{H}_5\text{OH}$)

80.1 lb. of sulphur trioxide (SO_3)

2,000 lb. of nitric acid (HNO_3)

13. What is the valence of iron (Fe) in each of the following compounds?

Ferrous chloride (FeCl_2)

Ferrous oxide (FeO)

Ferrie chloride (FeCl_3)

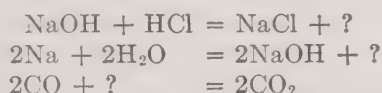
Ferrie oxide (Fe_2O_3)

14. What is the valence of sodium (Na) in each of the following compounds?

Sodium chloride (NaCl)

Sodium oxide (Na_2O)

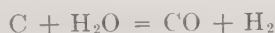
15. Balance the following equations:



16. In the reaction $\text{NH}_3 + \text{HCl} = \text{NH}_4\text{Cl}$, how many pounds of ammonium chloride (NH_4Cl) would be produced if 1 lb. mol of ammonia (NH_3) were completely converted to the chloride?

17. To produce 100 lb. of hydrogen sulphide (H_2S) by the reaction $\text{FeS} + 2\text{HCl} = \text{FeCl}_2 + \text{H}_2\text{S}$, how many pounds of hydrogen chloride (HCl) would be used up?

18. If carbon (C) at the proper temperature is in contact with steam (H_2O), the following reaction takes place:



Per ton of coke (assuming it to be 90 per cent carbon), how many pounds of CO and how many pounds of H_2 would be produced if this reaction goes to completion?

19. From 12,000 lb. of a shipment of impure sulphur, 34,400 lb. of 98 per cent sulphuric acid is produced. If each pound of 100 per cent sulphuric acid contains 0.816 lb. of SO_3 , what was the purity of the sulphur as received in the plant? Assume no mechanical losses.

20. A certain sample of a wet filter press cake shows by analysis, 28.4 per cent water, 63.6 per cent copper, and the balance oxygen. If the cake contains only water and a pure compound, what is the compound?

21. In hydrogen peroxide, there are twice as many pounds of oxygen per pound of hydrogen as in water. If 116 lb. of a solution contains 17 lb. of hydrogen peroxide and the balance is water, what is the total weight of oxygen and of hydrogen in the solution?

22. If 198 lb. of water is decomposed into hydrogen and oxygen, how much hydrogen sulphide (H_2S) could be produced from the hydrogen and how much cupric oxide from the oxygen, assuming complete conversion in each case?

23. Assume that copper costs 15 cents per pound and that processing it to either cuprous oxide (Cu_2O) or cupric oxide (CuO) costs 5 cents per pound of copper. How many pounds of Cu_2O could be made at a total cost of \$100 and how much CuO for the same cost?

24. If a ton of 98 per cent sulphuric acid were made from the impure sulphur in Prob. 19 at a cost of 1 cent per pound of 100 per cent pure acid and the raw material cost is 40 per cent of the total cost, how much was paid per ton of 100 per cent pure sulphur in the shipment? What was the cost per ton of impure sulphur?

25. If the impure sulphur can be bought at the dock for \$18 per ton and the pure sulphur at \$19 per ton, and the additional transportation charges are \$1 per ton in each case, what will be the gain or loss per ton of 98 per cent acid produced if the impure sulphur is used? Assume a processing cost (in addition to raw material) of 60 cents per ton of 98 per cent acid for either kind of sulphur.

26. If 10,000 lb. of copper at \$15 per 100 lb. is used in making cuprous oxide and the products include 500 lb. of copper scrap which can be sold at 5 cents per pound plus 600 lb. of off-grade cuprous oxide valued at 10 cents per pound of copper content, calculate the net cost per 100 lb. of good cuprous oxide, assuming a processing cost of 5 cents per pound of copper actually converted.

27. If cuprous oxide is produced by the complete conversion of 636 lb. of copper, how many pounds of oxygen will be used?

28. For the sulphur dioxide mentioned in Prob. 7, an excess of 20 per cent oxygen was used. What was the total oxygen usage?

29. If 100 gal. of certain liquids have the following weights each, what is the specific gravity of each liquid?

(a) 833 lb.

(b) 1,000 lb.

(c) 675 lb.

(d) 1,549 lb.

30. A certain vertical tank is 5 ft. in diameter and 6 ft. deep. How many pounds of water will it hold when half full? If filled within 6 in. of the top with a solution of specific gravity 1.2, how many pounds of solution are there?

31. If a 50-gal. barrel were filled with phenol (sp. gr. 1.07), how many pounds would it contain?

32. A kettle is filled to a depth of 6 ft. with 3,600 lb. of xylene (sp. gr. 0.875). Assuming a flat bottom, what is the diameter of the kettle?

33. At 40°F., 1 lb. of dry air occupies a volume of 12.6 cu. ft. at atmospheric pressure. How many pounds of dry air would there be in a room 16 by 12 by 10 ft. high?

34. Air saturated with water vapor, occupies a volume of 15.1 cu. ft. per pound of dry air at 100°F. The water vapor in this mixture (associated with 1 lb. of dry air) weighs 0.0431 lb. In a building 40 by 60 by 20 ft. high, how many pounds of dry air and how many pounds of moisture will there be under these conditions?

35. Convert the following temperatures into degrees Fahrenheit:

Examples: $10^{\circ}\text{C.} = 1.8 \times 10 + 32 = 18 + 32 = 50^{\circ}\text{F.}$

$-5^{\circ}\text{C.} = -1.8 \times 5 + 32 = -9 + 32 = 23^{\circ}\text{F.}$

(a) $104^{\circ}\text{C.} = \quad^{\circ}\text{F.}$

(b) $-40^{\circ}\text{C.} = \quad^{\circ}\text{F.}$

(c) $235^{\circ}\text{C.} = \quad^{\circ}\text{F.}$

36. Convert the following temperatures into degrees Rankine (the absolute temperature scale):

Examples: $110^{\circ}\text{F.} = 110 + 460 = 570^{\circ}\text{R.}$

$$5^{\circ}\text{C.} = (1.8 \times 5 + 32) + 460 = 9 + 32 + 460 = 501^{\circ}\text{R.}$$

$$-10^{\circ}\text{F.} = -10 + 460 = 450^{\circ}\text{R.}$$

$$-15^{\circ}\text{C.} = (-1.8 \times 15 + 32) + 460 = -27 + 32 + 460 = 465^{\circ}\text{R.}$$

$$(a) \quad 210^{\circ}\text{F.} = \quad^{\circ}\text{R.}$$

$$(b) \quad -150^{\circ}\text{F.} = \quad^{\circ}\text{R.}$$

$$(c) \quad 20^{\circ}\text{C.} = \quad^{\circ}\text{R.}$$

$$(d) \quad -100^{\circ}\text{C.} = \quad^{\circ}\text{R.}$$

$$(e) \quad -273^{\circ}\text{C.} = \quad^{\circ}\text{R.}$$

37. Convert the following pressures as indicated:

$$3 \text{ atmospheres} = \text{lb. per sq. in.}$$

$$299 \text{ in. of mercury} = \text{atmospheres}$$

$$678 \text{ ft. of water} = \text{lb. per sq. in.}$$

✓38. Temperature conversions:

$$50^{\circ}\text{C.} = \quad^{\circ}\text{F.} \quad 104^{\circ}\text{F.} = \quad^{\circ}\text{C.}$$

$$= \quad^{\circ}\text{R.} \quad -40^{\circ}\text{F.} = \quad^{\circ}\text{C.}$$

$$-50^{\circ}\text{C.} = \quad^{\circ}\text{F.} \quad -220^{\circ}\text{F.} = \quad^{\circ}\text{C.}$$

$$= \quad^{\circ}\text{R.}$$

$$150^{\circ}\text{C.} = \quad^{\circ}\text{F.} \quad 176^{\circ}\text{F.} = \quad^{\circ}\text{C.}$$

$$= \quad^{\circ}\text{R.} \quad 14^{\circ}\text{F.} = \quad^{\circ}\text{C.}$$

$$590^{\circ}\text{R.} = \quad^{\circ}\text{F.} \quad 672^{\circ}\text{R.} = \quad^{\circ}\text{C.}$$

$$420^{\circ}\text{R.} = \quad^{\circ}\text{F.} \quad 474^{\circ}\text{R.} = \quad^{\circ}\text{C.}$$

$$= \quad^{\circ}\text{C.} \quad 483^{\circ}\text{R.} = \quad^{\circ}\text{C.}$$

✓39. Specific gravities and densities:

$$10 \text{ gal. of water} = \text{lb.}$$

$$100 \text{ lb. of water} = \text{gal.}$$

$$= \text{cu. ft.}$$

$$1,000 \text{ lb. of aluminum} = \text{cu. ft.} \quad (\text{Take sp. gr. as } 2.65)$$

$$3 \text{ tons of copper ore} = \text{cu. ft.} \quad (\text{Take sp. gr. as } 4.2)$$

$$\text{pig iron} = \text{lb. per cu. ft.} \quad (\text{Take sp. gr. as } 7.2)$$

$$4 \text{ cu. ft. of lead} = 2,840 \text{ lb.} \quad \text{What is sp. gr. ?}$$

$$1 \text{ cu. ft. of mercury} = 849 \text{ lb.} \quad \text{What is sp. gr. ?}$$

$$100 \text{ tons of sulphur} = \text{cu. ft.} \quad (\text{Take sp. gr. as } 2.0)$$

$$100 \text{ tons of } 60\% \text{ H}_2\text{SO}_4 = \text{cu. ft. at } 20^{\circ}\text{C.} \quad (\text{Take sp. gr. as } 1.50)$$

$$1,000 \text{ lb. of } 40\% \text{ HNO}_3 = \text{gal. at } 10^{\circ}\text{C.} \quad (\text{Take sp. gr. as } 1.26)$$

$$1,800 \text{ lb. of } 8\% \text{ CuSO}_4 = \text{gal. at } 20^{\circ}\text{C.} \quad (\text{Take sp. gr. as } 1.08)$$

40. Superheated steam (atmospheric pressure, 250°F.) occupies 27.8 cu. ft. per pound. How many pounds of this are there in a line 12 in. by 500 ft. long?

Superheated steam at 400°F. occupies 34.0 cu. ft. per pound. How many pounds are there in the same steam line as above?

Dry air at 70°F. atmospheric pressure, has a specific volume of 13.4 cu. ft. per pound. If a tank is 10 ft. in diameter by 12 ft. deep, how many pounds of dry air at 70° would it hold? How many pounds of water?

Liquid ammonia at -100°F. weighs 45.0 lb. per cubic foot. What is its specific gravity? At +100°F., it weighs 36.3 lb. per cubic foot. What is its specific gravity?

41. Pressures:

100	lb. per sq. in.	=	ft. of water
		=	ft. of mercury
		=	atmospheres
3.5	atmospheres	=	lb. per sq. in.
		=	lb. per sq. ft.
59.8	in. of mercury	=	ft. of water
		=	lb. per sq. in.
88.2	lb. per sq. in.	=	atmospheres
2,880	lb. per sq. ft.	=	atmospheres
		=	ft. of water
15	in. of mercury	=	ft. of water
144	lb. per sq. ft.	=	in. of mercury
10	ft. of mercury	=	lb. per sq. ft.

42. Heat content (specific heats). Specific heats of various substances are:

Gases:

Air	= 0.238 at 0°C.
Superheated steam	= 0.50 (approximately)
CO ₂	= 0.178
SO ₂	= 0.120

Liquids:

Acetone	= 0.510 (20°C.)
Benzene	= 0.419 (30°C.)
Ether	= 0.525 (-5°C.)
Glycerin	= 0.576 (35°C.)
Methanol	= 0.590 (10°C.)
Rosin	= 0.525 (20-245°C.)

Solids:

Calcium oxide	= 0.172
Silica	= 0.183
Zinc oxide	= 0.121
Cuprous oxide	= 0.111
Cupric oxide	= 0.142
Naphthalene (solid)	= 0.281
Urea	= 0.320
Silver	= 0.055
Copper	= 0.091

Iron	= 0.116
Aluminum	= 0.209
Lead	= 0.030

Calculate the heat required to raise 100 lb. of each of the above materials from 50 to 90°F.

43. How much heat is required to raise the temperature of a batch of rosin from 200 to 450°F., if it is contained in a tank 10 ft. in diameter by 18 ft. 6 in. long, assuming the tank to be 75 per cent full and neglecting curvature of the ends? Take the specific gravity as 1.

44. If a tank car of glycerin contains 60,000 lb. which is to be heated from 32 to 70°F., how much heat is required?

45. How much heat is given up in cooling 1 ton of lime (CaO) from 400 to 70°F.? How much in cooling 1 ton of copper through the same range?

46. If 10,000 lb. of benzene is to be cooled from 50 to 10°C., how much heat must be removed? If this is done with cooling water entering coils at 40°F. and leaving at 60°F., how many gallons of water are needed?

47. If 1 ton of sand (assumed as silica) is at a temperature of 350°F. and is dumped into 1,000 gal. of water at 70°F., what is the final temperature of the sand and water, neglecting any radiation losses?

48. If 1,000 lb. of steam at atmospheric pressure is condensed per hour in the coils of a still, how many pounds of benzene could be vaporized, assuming 10 per cent of the heat is lost by radiation?

49. How much steam at atmospheric pressure is required to boil off 50 per cent of the methanol from a batch of recovered methanol which has been contaminated by a trace of grease, assuming that the still is a horizontal cylinder 5 ft. in diameter by 10 ft. long, filled half full? Neglect curvature of ends and assume 5 per cent radiation loss. The specific gravity of the batch may be taken as 0.78 at the boiling point.

50. What is the cost of evaporating 750 lb. of benzene from a wet cake, using atmospheric pressure steam which costs 20 cents per 1,000 lb.? The radiation loss may be neglected.

51. Taking the specific heat of methanol as 0.6, how much heat is required to heat 2,000 lb. of it from 60°F. to the boiling point and to evaporate 40 per cent at atmospheric pressure?

52. If the heat for Prob. 51 were supplied by benzene vapor, assuming 5 per cent radiation loss, how many gallons of benzene would be condensed, taking the specific gravity of benzene as 0.87?

53. What is the vapor pressure of water, expressed in inches of mercury, at 118°F. and at 190°F.?

54. How much steam would be required to melt 1 ton of sulphur and to heat it to 300°F., taking the specific heat of the liquid sulphur as 0.4, the melting point as 235°F., and the latent heat of the steam at this temperature as 872 B.t.u. per pound? Assume 15 per cent radiation loss and that the sulphur is already heated to 235°F.

55. If 1,500 lb. of molten sulphur at 275°F. is sprayed with water so that the sulphur solidifies and cools to 220°F., how much water would be evaporated? Neglect heat losses to the air. Take the specific heat of the solid as 0.35 and the temperature of the water as 70°F.

56. When 1,000 lb. of benzene vapor is condensed in a coil, using 10 gal. of water per minute which enters at 40°F. and leaves at 65°F., and the benzene is cooled to 80°F., how much water is used?

57. How much ice would be required to cool 500 lb. of benzene from 80 to 42°F. and freeze 20 per cent of it? Assume that ice water flows away as soon as formed.

58. A kettle containing water and water vapor only at 164°F. (boiling under vacuum) has a manhole with a cover having an area of 1.2 sq. ft. How much force would be required to pull the cover off?

59. If the temperature of the water boiling in this kettle is raised to 190°F., how much force will have to be applied to pull the cover off?

60. At what temperature would you estimate that water boils under a vacuum of 10 in. of mercury? Under a vacuum of 26 in. of mercury?

61. If 100 lb. of a certain gas has a volume of 1,400 cu. ft. at 32°F. and atmospheric pressure, what will be the volume at 32°F. and 29.4 lb. per square inch?

62. What would be the pressure of this gas if its volume were increased to 2,100 cu. ft., at 32°F.?

63. At a given temperature, 10 lb. of a certain gas has a volume V_1 at a pressure P_1 . If the volume is changed to V_2 , show that the new pressure $P_2 = (V_1/V_2)P_1$.

64. If the pressure is now changed to P_3 , show that the new volume $V_3 = (P_2/P_3)V_2$.

65. If the ratio $P_1/P_2 = 5$ in Prob. 63, what is the value of ratio V_1/V_2 ?

66. At 524°F., 58 lb. of air at a pressure of 29.9 in. of mercury has a volume of 718 cu. ft. If the gas is compressed to 359 cu. ft. at the same temperature, what is the pressure in atmospheres?

67. If the air pressure is now increased to 100 lb. per square inch, what will the volume be, keeping the temperature constant?

68. What is the volume of 56 lb. of nitrogen gas (N_2) at standard conditions?

69. How many pounds of oxygen gas (O_2) are there in 1,436 cu. ft. at standard conditions?

70. At 29.9 in. mercury pressure and 0°C., what is the volume of 142 lb. of chlorine gas (Cl_2)?

71. For 4 lb. of hydrogen at standard conditions, find the value of K in the expression of Charles's law, $pV = KT$. Use p in atmospheres, V in cubic feet, T in degrees Rankine.

72. What is the volume of this hydrogen at 200°F. and atmospheric pressure?

73. What is the pressure if the same amount of hydrogen at 200°F. is compressed into 25 per cent of the volume found in Prob. 72?

74. If 84 lb. of nitrogen occupies 1,077 cu. ft. at standard conditions, what is the volume of this gas at 100°F., when compressed to 3 atmospheres?

75. Calculate the value of K in Charles's law for 16 lb. of hydrogen, for 128 lb. of oxygen, and for 71 lb. of chlorine, each at standard conditions. What is the ratio of K for hydrogen to K for oxygen in this case? What is the ratio of K for hydrogen to K for chlorine?

76. A closed vessel contains absolutely dry air ("bone-dry") at 164°F . and at a pressure of 10 lb. per square inch. Hot water is sprayed into the chamber under such conditions that several hours later there is a small pool of water on the floor of the vessel and both water and air are still at 164°F . What is the total pressure in the vessel? Why?

77. A 10 cu. ft. tank contains oxygen at 25 lb. per square inch pressure at temperature t . Another 10 cu. ft. tank contains nitrogen at 75 lb. per square inch, the temperature being the same as in the oxygen tank. If a valve is opened between the tanks and the gases mix completely by *diffusion*, the temperature remaining constant, what will be the total pressure on each tank? Why?

78. A tank contains moist air at a pressure of 30 lb. per square inch. By suitable measurements, we find that there are approximately 4 mols of oxygen, 16 mols of nitrogen, and 10 mols of water vapor in the vessel. If only the nitrogen were left in the vessel, keeping the temperature constant, what would be its pressure?

79. If only the nitrogen were removed from the tank in Prob. 78, keeping the temperature constant, what would be the total pressure? What is the "mol fraction" of oxygen in this case? What was its mol fraction when all three gases were present?

80. In a gas mixture containing 142 lb. of chlorine, 56 lb. of nitrogen, and 96 lb. of oxygen, what is the mol fraction of the chlorine? If the pressure were decreased by 60 per cent by opening into another tank, previously *evacuated* completely, what would be the mol fraction of the chlorine?

81. If a certain tank contains 48 lb. of oxygen at 100°F . and 100 lb. per square inch pressure, what is the volume of the tank?

82. Fifty-six pounds of nitrogen is pumped into a tank having a volume of 30 cu. ft. If the temperature is 40°F ., what pressure is required?

83. What is the pressure in atmospheres of a gas holder containing 10,000 cu. ft. of methane gas (CH_4) at 100°F ., the density of the gas being 0.04 lb. per cubic foot under these conditions?

84. A certain compound contains 92.25 per cent carbon and 7.75 per cent hydrogen by weight. Its density in the form of vapor at 100°C . and 1 atmosphere pressure is determined to be 2.47 times that of oxygen under the same conditions. What is its molecular weight? Write its formula.

85. Air is found to contain 79.1 per cent nitrogen and 20.9 per cent oxygen by volume. What is the weight of 35,900 cu. ft. of air at 32°F . and 1 atmosphere pressure?

86. Taking 29 lb. as the weight of 1 lb. mol of air, how many cubic feet of air are contained in a vessel holding 58 lb. of air at a temperature of 50°C . and a pressure of 5 atmospheres?

87. How many pounds of air at a total pressure of 229 lb. per square inch and a temperature of 110°F . can be compressed into a receiver 2 ft. in diameter and 10 ft. long?

88. If 1 lb. of air is compressed into a volume of 2 cu. ft. at 60°F ., what must be the pressure in inches of mercury?

89. When 2,154 cu. ft. of ethylene gas (C_2H_4) at standard conditions is pumped into a 200-gal. tank at 160°F ., what is the pressure and how many pounds of gas are there?

90. Hydrogen gas is formed by decomposing 1,000 gal. of water in an electrolytic cell. It is then compressed to 4,000 lb. per square inch at 20°C. What is its volume?

91. What is the temperature of a 1,000-gal. tank containing 74 lb. of nitrogen at a pressure of 147 lb. per square inch?

92. Gas from a certain sulphur burner contains 12 per cent sulphur dioxide by volume. At 200°C. and atmospheric pressure, how many cubic feet of gas are produced from the combustion of 642 lb. of pure sulphur?

93. If the gas produced in Prob. 92 were compressed to 29.4 lb. per square inch *above* atmospheric pressure at 100°F., what would be its volume?

94. According to the reaction, $\text{CaCO}_3 + 2\text{HCl} = \text{CaCl}_2 + \text{H}_2\text{O} + \text{CO}_2$, 88 lb. of carbon dioxide is formed by treating calcium carbonate with hydrochloric acid. What is the volume of the dry carbon dioxide finally obtained at a pressure of 1 ft. of water above atmospheric pressure and a temperature of 50°F.? How many pounds of hydrochloric acid were consumed?

95. If the hydrochloric acid had been introduced as a mixture of 80 per cent air, 20 per cent HCl, how many cubic feet of this mixture had to be conveyed if the temperature was 40°F. and the pressure 1 lb. per square inch above atmospheric?

96. The airship Zeppelin II contained 16 balloonettes which were filled with 460,000 cu. ft. of hydrogen at 70°F. and atmospheric pressure. The total weight of the zeppelin was

	Pounds
Engines.....	1,100
Gasoline for 60 hr.....	13,200
Crew of 15 men.....	2,250
Frame, covering, ballast, etc.....	15,000

Find the pull on the anchor ropes. (Note that a body in a fluid, either liquid or gas, is buoyed up by a force equal to the weight of fluid displaced.)

97. If 100 lb. of propane (C_3H_8) is burned completely with air in accordance with the reaction $\text{C}_3\text{H}_8 + 5\text{O}_2 = 3\text{CO}_2 + 4\text{H}_2\text{O}$, how many pounds of flue gas will leave the furnace if the air used is 50 per cent over theory? Take the analysis of air as 79.1 per cent nitrogen, 20.9 per cent oxygen, by volume.

98. The flue gas from Prob. 97 is cooled to 300°F. at atmospheric pressure. What is the diameter of the pipe leaving the cooler if the velocity of the cooled gas is 10 ft. per second? The propane is burned in 1 hr.

99. Taking the specific heat of the flue gas as 0.32, how much heat was removed by the cooler if the gas entered at 2000°F?

100. A 50-gal. tank, weighing 125 lb. when empty, is filled with nitrogen gas at 70°F. and 200 lb. per square inch pressure. The tank accidentally falls into a river. Will it sink?

101. When 1 lb. of 100 per cent sulphuric acid is diluted to the following concentrations, the amount of heat evolved and the average specific heat of the given strength acid are as follows:

Per cent	Heat evolved, B.t.u.	Specific heat
20	300	0.85
40	270	0.70
60	218	0.57
80	140	0.48
90	80	0.45

Calculate:

- Pounds of diluted acid per pound 100 per cent in each of above cases.
- Heat evolved per pound of diluted acid.
- Rise in temperature in each case, assuming that the 100 per cent acid was added at the same temperature as the water of dilution.

102. If 500 lb. of 100 per cent sulphuric acid at 70°F. is diluted to 40 per cent by adding it to a mixture of water and ice at 32°F., how many pounds of ice would be required so that the temperature would not rise above 50°F.? Above 75°F.?

103. If the 40 per cent sulphuric acid in Prob. 102 were diluted with water at 50°F. so that the final concentration became 20 per cent, how much would the resulting solution rise in temperature? How many pounds of 20 per cent acid would there be? Assume 40 per cent acid is at 50°F.

104. If 1,000 lb. of a saturated solution of sulphur in carbon disulphide (CS_2) at 122°F. is cooled to 104°F., how many pounds of sulphur could be filtered out? What per cent solution remains?

105. Seventy-seven pounds of carbon disulphide is heated with an excess of sulphur at 50°F. How many more pounds of sulphur would this solution contain if it were heated to 104°F.?

106. Per pound mol of caustic soda (NaOH) per 1,000 lb. of water, what is the B.P.R. in degrees Fahrenheit for each of the concentrations given on page 21?

107. A mixture of ice and salt finally begins to freeze at -6°F . What is the concentration of the salt solution at this point?

108. Sea water contains 3.6 per cent solids, of which about 2.8 per cent is common salt (NaCl). If the other solids are assumed to have a molecular weight of 100 and to have a normal effect (like sugar) on freezing point lowering, at what temperature would the sea water freeze?

109. If calcium chloride (CaCl_2) has twice the molecular freezing point lowering of NaCl , what would be the freezing point of 1,000 lb. of water containing 100 lb. of CaCl_2 and of 1,000 lb. of water containing 100 lb. of NaCl ? The atomic weight of calcium is 40.1.

110. If 1,000 lb. of water is saturated with CaCl_2 at 18°C ., and enough sodium carbonate is added to complete the reaction $\text{CaCl}_2 + \text{Na}_2\text{CO}_3 = \text{CaCO}_3 + 2\text{NaCl}$, how many pounds of calcium carbonate would remain in solution? How much would be precipitated as solid?

CHAPTER II

TRANSFORMATION OF ENERGY

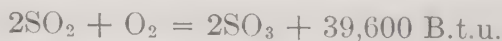
Energy, as delivered to the operating department of a plant, may be in the form of latent heat in steam, as electrical energy, as latent energy in fuel, etc. To utilize it, this energy must usually be *transformed* into another form. Thus, many reactions require the addition of heat to make them "go"; others require mechanical energy to secure intimate mixing of the raw materials, and still others require the removal of heat. Consequently, the supervisor of the department needs to have a clear understanding of the fundamental principles involved in these transformations.

CHEMICAL ENERGY AND HEAT

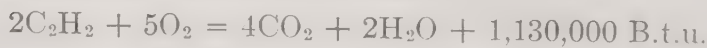
Heat of Reaction.—Every chemical reaction involves heat. If heat is evolved, the reaction is said to be *exothermic*; if absorbed, *endothermic*. By considering the chemical equation that represents the reaction in question as expressing pound atoms and pound molecular quantities, the heat effect can be expressed as B.t.u. evolved or absorbed (+ or -).

Examples of exothermic reactions are:

1. Oxidation of sulphur dioxide to sulphur trioxide:



2. Burning of acetylene with oxygen:

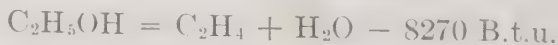


3. Formation of hydrochloric acid from hydrogen and chlorine:

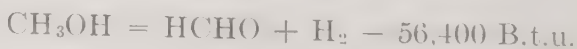


Examples of endothermic reactions are:

1. Formation of ethylene from ethanol:



2. Formation of formaldehyde from methanol:



3. Formation of isobutylene from isobutane:



Combustion of Fuels.—When the principal object of carrying out a reaction between oxygen and another substance is to obtain the heat of reaction, such a substance is called a *fuel*, and the reaction, which is accompanied by both light and heat, is called *combustion*. Fuels are classified as *primary* or *secondary* according to whether they are used as found in nature or must first be processed to put them into the desired condition. Thus, primary fuels include natural gas, wood, and coal. Secondary fuels include producer gas, coke-oven gas, blue water gas, petroleum distillates, and coke.

For gaseous fuels, the heat evolved is usually expressed as B.t.u. per cubic foot of gas at normal temperature and pressure; liquid fuels are rated in B.t.u. per gallon or per pound and solid fuels in B.t.u. per pound. These heats of reaction are obtained by burning the fuel in a *calorimeter* and cooling the products of reaction down to the original temperature, absorbing the heat in cooling water, whose increased heat content is a measure of the heat evolved.

For gases whose products of combustion contain considerable amounts of water, owing to hydrogen in the original gas, it is customary to state the complete heat of reaction (as determined by the method mentioned above) as the gross or *higher heating value*. This value is corrected by subtracting from it the latent heat of its water content which is not usually recoverable, since products of combustion are normally discarded at temperatures far above the *dew point* of the gases. This corrected value is called the *net* or *lower heating value*.

Natural Gas.—The composition of natural gas varies over a wide range, usually including methane (CH_4), ethane (C_2H_6), and propane (C_3H_8) in widely different proportions. A “representative” sample of a West Virginia gas was found to have 31.8 per cent ethane, 77.7 per cent propane, and 0.5 per cent nitrogen, the upper and lower heating values being 2469 B.t.u. per cubic foot and 2268 B.t.u., respectively. A Pennsylvania gas showed 32.3 per cent methane, 67.0 per cent ethane, and 0.7 per cent nitrogen, the heating values being (gross) 1482 B.t.u. per cubic foot and (net) 1350 B.t.u. Still another analysis was found for

an Ohio gas, which contained 83.5 per cent methane, 12.5 per cent ethane and 4.0 per cent carbon dioxide and nitrogen. Its gross heating value was 1047 B.t.u. per cubic foot and its net value was 946. These analyses, together with those for other fuels, quoted later in this chapter, are given by Haslam and Russell in "Fuels and Their Combustion," McGraw-Hill Book Company, Inc., New York, 1926. The heating values are based on 1 cu. ft. at 60°F., at 30 in. of mercury, saturated with water vapor.

Coal.—The other important primary fuel is coal, classified as *anthracite* or *bituminous* according to whether it is mainly carbon or whether it contains considerable quantities of *hydrocarbons*, compounds of carbon and hydrogen which are vaporized or *volatilized* when the coal is fed into a furnace. Since the same fuel may be received with a small or large amount of moisture, depending upon the exposure of the coal car to weather en route, it is customary to report analyses on a "dry" basis. In Table VIII, the inert matter or *ash* has also been eliminated so that the comparison of typical Pennsylvania bituminous and Pennsylvania anthracite coals may be made on the basis of their *combustible* content.

As indicated in the table, a "proximate analysis" shows what per cent of a dried coal sample can be *volatilized* (driven off as vapor) by heating in a closed crucible at 1740°F. for a specified time. The amount of the unvaporized material that can then be burned in the presence of air (*i.e.*, with the lid off the crucible) is called *fixed carbon* and the nonvolatile, noncombustible, residue is the *ash*. The complete, or "ultimate," analysis, a more time-consuming operation, involves determination by chemical means of the proportions of the individual elements in the coal.

Producer Gas.—This is an important secondary fuel. It is made by blowing a mixture of air and steam through a very hot bed of coal. The principal chemical reactions involved are discussed later in this chapter. A typical analysis is given in Table IX.

Coke-oven Gas.—When coal is subjected to high temperatures in ovens out of contact with the air, volatile matter, produced by the breaking down of compounds in the coal, is driven off through pipe lines. Tar, ammonia, and various other compounds are removed from the gas by cooling and scrubbing it, the final gas

being thus made available as a fuel. The nonvolatile content of the coal (carbon and ash) is then pushed out of the ovens as *coke*. Such an operation is called *destructive distillation*. See Table IX for data on the composition and heating value of the gas. A coke containing about 10 per cent ash has a heating value of about 13,000 B.t.u. per pound as received in a plant.

TABLE VIII.—COMPARISON OF TYPICAL COALS*
(Exclusive of ash and moisture)

Analyses	Bituminous	Anthracite
Proximate Analysis:		
Volatile matter.....	30.2 %	6.2 %
Fixed carbon.....	69.8	93.8
Total.....	100.0 %	100.0 %
Ultimate Analysis:		
Sulphur.....	1.0 %	0.6 %
Hydrogen.....	5.8	2.7
Carbon (total).....	86.7	94.0
Nitrogen.....	1.4	1.0
Oxygen.....	5.1	1.7
Total.....	100.0 %	100.0 %
Heating value in B.t.u. per lb. of coal, exclusive of ash and moisture.....	15,500	14,000
Usual range of moisture content of coal as received.....	2-10 %	2-4 %
Usual range of ash content of coal as received..	2-12 %	1.5-10 %

* Robert T. Haslam and Robert P. Russell, "Fuels and Their Combustion," McGraw-Hill Book Company, Inc., New York, 1926.

Blue Water Gas.—Owing to the presence of nitrogen in the air used to make producer gas, the resultant gas contains a considerable amount of the noncombustible nitrogen. To obtain a richer gas with a minimum amount of inert material, a special type of fuel, called *blue water gas*, is obtained by blowing steam through an incandescent bed of carbon until the temperature falls to a predetermined point, then blowing air through the bed to reheat it by combustion of some of the carbon. The combustion products obtained during this heating period are, of course, led off through a separate main. When the bed is again at the desired high temperature, air is shut off and steam turned on again to repeat the cycle.

Petroleum Distillates.—The refining of crude petroleum involves distilling off the various portions of the material, collecting the low-temperature distillate as gasoline, a higher boiling material as kerosene, still higher boiling liquids as gas oil and lubricating oils. In the further processing of these distillates, a large amount becomes available for fuels, ranging from a very viscous "bunker C oil" to a thin light-colored domestic furnace oil. The heating value of oils varies between about 18,000 and 19,500 B.t.u. per pound. Since oil is sold by the gallon, it should be noted that the B.t.u. per gallon is higher for the oils of higher specific gravity (low Baumé) than for the lighter (high Baumé)

TABLE IX.—TYPICAL MANUFACTURED GASES*

Composition	Coke oven	Producer	Blue water
Methane (CH ₄).....	28.5 %	2.6 %	
Ethylene (C ₂ H ₄).....	2.9	0.4	
Carbon monoxide (CO).....	5.1	22.0	43.4 %
Carbon dioxide (CO ₂).....	1.4	5.7	3.5
Hydrogen (H ₂).....	57.4	10.5	51.8
Oxygen (O ₂).....	0.5		
Nitrogen (N ₂).....	4.2	58.8	1.3
Total.....	100.0 %	100.0 %	100.0 %
Heating value per cu. ft. at 60°F., 30 in. of mercury and saturated with water:			
Gross, B.t.u.....	536	136	310
Net, B.t.u.....	476	128	285

* Haslam and Russell, "Fuels and Their Combustion."

products, even though the latter have more heating value per pound.

Combustion Reactions.—In the burning of a fuel, various reactions are proceeding simultaneously but at rates varying individually according to conditions favoring or retarding each one. All of them, however, are *gas reactions*, *i.e.*, every important reaction in a furnace involves a gas and a solid or two or more gases with each other. Accordingly, the general statement, based on knowledge of all gas reactions, can be made that they are all relatively slow compared to liquid phase reactions, that they are accelerated by higher temperatures, and that they are also speeded up by

contact with hot solid surfaces. It is to be noted further that reactions which liberate heat tend to reverse themselves, *i.e.*, proceed from the right-hand side of the equation to the left, at higher temperatures.

The principal combustion reactions are usually stated as:

1. $C + O_2 = CO_2 + 176,600 \text{ B.t.u.}$
2. $C + CO_2 = 2CO - 70,200 \text{ B.t.u.}$
3. $2C + O_2 = 2CO + 104,400 \text{ B.t.u.}$
4. $2CO + O_2 = 2CO_2 + 244,800 \text{ B.t.u.}$
5. $2H_2 + O_2 = 2H_2O + 246,200 \text{ B.t.u.}$
6. $C + H_2O = CO + H_2 - 70,900 \text{ B.t.u.}$
7. $C + 2H_2O = CO_2 + 2H_2 - 71,600 \text{ B.t.u.}$
8. $CO + H_2O = CO_2 + H_2 - 700 \text{ B.t.u.}$

Of these, reaction 1 is rapid above 1500°F. and does not reverse itself appreciably at temperatures obtained in a furnace. Reaction 2 is slow relative to reaction 1, goes quantitatively to the right above 1800°F. and to the left below 900°F. That is, above 1800°F. , the amount of carbon dioxide that can exist in contact with carbon is small, whereas the reverse is true at lower temperatures where carbon cannot reduce CO_2 to CO . Reaction 3, like reaction 2, is relatively slow. Since these three reactions ordinarily involve solid carbon in coal, the rates are proportional to the amount of exposed carbon surface. Reactions 4 and 5, being all gaseous, are quite slow and must be given time for completion, by having adequate combustion space, before leaving the hot furnace.

Combustion Practice.—For maximum utilization of energy, it is obviously important to convert all the carbon in the fuel to CO_2 . Although reaction 1 is rapid, some CO is sure to form by reactions 2 and 3. To get this burned to CO_2 , the gas must be kept hot as long as possible after leaving the solid carbon, preferably by having it in contact with hot furnace walls and with an adequate supply of oxygen. On the other hand, when the desired product is CO , the CO_2 formed by reaction 1 must be kept in contact with hot carbon long enough for reaction 2 to take place, this being accomplished by having a thick bed of hot fuel through which the gas passes before leaving the system.

In making producer gas, the CO_2 from reaction 1 must be reduced to CO and the steam for reaction 6 needs a long time of contact with hot carbon to produce hydrogen. Also the CO_2

from reaction 7 needs time for reduction to CO. All of this is accomplished by having a very deep, hot fuel bed. Since reactions 2 and 6 *consume* heat, air is admitted to supply this heat by reaction 3. Thus, heat evolved by reactions 1 and 3 balances that absorbed by reactions 2 and 6. The only disadvantage is the dilution of the resultant gas by the nitrogen coming in with the air (about 4 mols per mol of oxygen).

When gas of low nitrogen content is desired (as in making blue water gas), reaction 6 is used by passing superheated steam through a thick bed of white-hot coal. The rapid absorption of heat cools the bed, so that the steam must be shut off periodically and air introduced to cause reheating by reaction 1. To avoid the formation of CO_2 by reaction 7 and to get steam decomposed without destroying the furnace, the temperature must be held between 1800 and 2300°F. The reversal of steam and air is usually made every 2 to 4 min.

Although heat transfer is to be discussed in some detail in a later chapter, it is necessary to mention here that one of the most effective means of transfer is by radiation of energy from glowing solids, whereas transfer from a gas is relatively slow. A great deal of heat may be transferred in a coal-fired furnace by direct radiation from the glowing fuel bed to that portion of the boiler tubes that can "see" the carbon. In burning gases, one method is to have an accurately proportioned mixture of fuel and air introduced through a porous solid so that immediate combustion takes place on the extended surfaces of the solid. This *surface combustion* permits very rapid transfer of heat by radiation from the incandescent solid to the boiler tubes or other receiver of energy.

Another method of utilizing radiation as a means of increasing the rate of heat transfer and thereby reducing the amount of surface needed is to burn a high volatile fuel. This permits adjustment of the air so that a slightly smoky flame is produced, the carbon particles of which become incandescent and act as a large radiating surface.

Long Flame.—Instead of a short flame of very high localized temperature, it is sometimes necessary to have a long flame in order to distribute heat energy at a relatively low but uniform temperature over a large area of material being heated. By having only partial combustion of the fuel in the main furnace

chamber, the gas produced will contain large amounts of CO . Additional air is then introduced to burn this to CO_2 farther on in the apparatus. As noted previously, the formation of the CO is

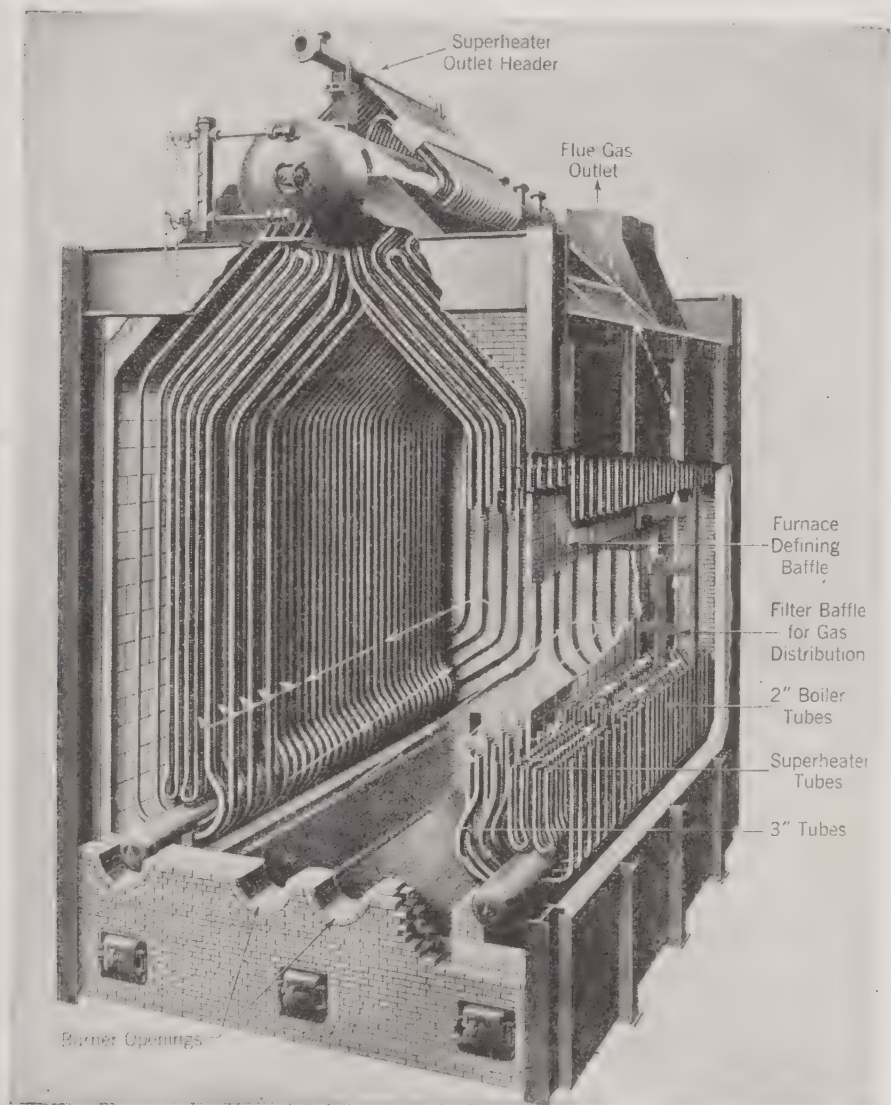


FIG. 1.—A modern steam generator. (Courtesy of Foster Wheeler Corporation.)

avored by using a thick fuel bed and by injecting steam to give reaction 3. The long flame, produced by slow combustion to CO_2 and H_2O as secondary air is added, is thus carried in contact with the material being heated. Another way to get this result is to recirculate some flue gas from the end of the unit, mix it with the

entering air, and thus allow reaction 2 to absorb some of the heat evolved by reaction 3. This procedure is utilized in certain types of lime kilns where the use of too hot a flame in contact with the limestone produces an inferior, overburned lime.

Liquid Fuels.—The combustion of liquid fuels is very flexible and rapid. Since it is important that every particle of oil should burn or at least be completely vaporized before striking any solid surface, the combustion space must be large enough to permit this. The oil is atomized and sprayed as a fine mist, intimately mixed with air, into the chamber. If liquid particles strike the walls, they remain at their boiling point until completely vaporized, thus cooling the walls to a relatively low temperature, reducing combustion rates, and promoting “coking” of the oil.

Powdered Fuels.—The use of powdered coal has become increasingly popular because of its flexibility and speed and the possibility of using cheap coal of high ash content. However, maintenance of grinding equipment is quite expensive, and there is a considerable explosion hazard. Although the choice of such equipment is not within the province of the operating man, he should recognize these factors and give attention to them in his control of the equipment.

Gaseous Fuels.—To effect the combustion of gaseous fuels with air, there must be a mixture that will ignite, and that mixture must be supplied with enough heat to bring it to the ignition temperature. For each kind of gas there is a range of concentration within which the heat liberated at ignition is sufficient to heat the remainder of the mixture fast enough to keep combustion in progress. Above and below the limits of this range, the diluent effect of the unburned gases is so great that the flame will go out. Table X shows (the upper and lower percentages of gas in air at atmospheric pressure within whose range combustion will proceed without external heat supply.)

The *ignition temperature*, to which a mixture of gas and air must be heated in order that it will continue to burn without external heat supply, is quite different for different materials. Table XI gives data selected from a more extensive table in Haslam and Russell’s “Fuels and Their Combustion,” showing the ignition temperatures of several gases as well as of some liquids and solids. For most substances, the ignition temperature is lower at increased pressures. Thus, in a gas engine, where the

charge is compressed and thereby heated before firing, it is important that the fuel be such that it will not ignite prematurely under compression. From the lowered ignition temperatures noted when pure oxygen is used instead of air, it will be obvious that great care must be exercised in the handling of oxygen under pressure. Oiling of valve stems and of stuffing boxes on vessels carrying oxygen is hazardous because of the low temperature required to start combustion as well as because of possible reactivity of the oil and oxygen at even lower temperatures.

TABLE X.—COMBUSTIBLE MIXTURES*
(Per cent of gas by volume in gas-air mixture)

Gas	Lower limit, %	Upper limit, %
Hydrogen (H ₂).....	6.2	71.4
Carbon monoxide (CO).....	16.3	71.2
Coke-oven gas.....	7.0	21.0
Methane (CH ₄).....	5.8	13.3
Ethyl alcohol (C ₂ H ₅ OH).....	3.7	13.7
Benzene (C ₆ H ₆).....	1.4	5.5
Ether (C ₂ H ₅) ₂ O.....	1.6	7.7

* Haslam and Russell, "Fuels and Their Combustion."

TABLE XI.—IGNITION TEMPERATURES*

Substance	In air, °F.	In oxygen, °F.
Hydrogen.....	1076-1094	1076-1094
Carbon monoxide.....	1191-1216	1179-1216
Methane.....	1202-1382	1033-1292
Acetylene (C ₂ H ₂).....	763-824	781-824
Benzene.....	1364	1224
Ethyl alcohol.....	1036	797
Glycerin.....	932	777
Acetone.....	1292	1054
Sugar.....	725	712
Cylinder oil.....	783	608
Kerosene.....	563	518
Gas oil.....	637	518

* Haslam and Russell, "Fuels and Their Combustion."

Flame Velocity.—The speed with which a flame will travel through a mixture of air and gas varies with the kind of gas, the

percentage of it in the mixture, and the size of the container. For small tubes, the velocity is decreased, whereas it is greater with larger tubes. Table XII shows the percentage of several types of gas-air mixtures which give the highest velocity. In most cases, this "maximum-speed mixture" contains about 15 per cent *more* gas than needed for complete combustion. It is of interest to note that for all gases which are just at their lower or their higher limits of inflammability (*e.g.*, hydrogen at 6.2 per cent or at 71.4 per cent; carbon monoxide at 16.3 per cent or at 71.2 per cent) the speed is about 0.65 ft. per second. This should be compared with their maximum rates, as shown in the table.

Theoretical Temperature.—If a fuel could be burned completely and instantaneously with theoretical quantities of air and without loss of heat to surroundings, the resultant temperature of the combustion products would evidently be the maximum attainable with that fuel and air. This *theoretical flame temperature* for any fuel is calculated by dividing the total heat in the initial gaseous mixture (heat of combustion plus sensible heat content of fuel and air) by the heat capacity of the products of combustion (pounds of products $\times$ average specific heats). Although this temperature cannot be attained in actual practice, it is useful as a basis for comparing different fuels. Table XIII shows the theoretical flame temperatures of several gases, their heating values, and the cubic feet of air theoretically required per cubic foot of each gas.

TABLE XII.—VELOCITY OF FLAME TRAVEL*

Gas	Rate, ft. per sec.	Gas in mixture, %
Hydrogen.....	15.9	38.5
Carbon monoxide.....	4.1	50.0
Methane.....	2.2	9.9
CO + H (equal volumes).....	10.3	44.0
Producer gas.....	2.4	51.0

* Haslam and Russell, "Fuels and Their Combustion."

Heating Value of Mixtures.—To calculate the heating value of a mixture of any gas with the theoretical amount of air

required for complete combustion, Haslam and Russell give the following formula:

B.t.u. per cu. ft. of mixture

$$= \frac{100 \text{ (net heating value per cu. ft. of pure gas)}}{(\text{net heating value per cu. ft. pure gas}) + 50}$$

ILLUSTRATIVE PROBLEMS

In solving the problems relating to chemical energy and heat, the student will find it necessary to use many of the relationships that were pointed out in Chap. I. Since most of the work on combustion requires calculation of gas weights and volumes, the Law of Perfect Gases is of especial importance.

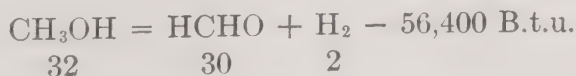
TABLE XIII.—HEATING EFFECT OF GASES*

Fuel	Net heating value per cu. ft., B.t.u.	Cu. ft. of air per cu. ft. of gas	Theoretical flame temperature, °F.
Coke-oven gas.....	476	4.65	3430
Blue water gas.....	285	2.28	4167
Producer gas.....	128	1.08	3050
Natural gas (Pa.).....	1350	14.25	3770

* Haslam and Russell, "Fuels and Their Combustion."

Illustration 1.—If the heat of formation of formaldehyde had to be supplied by burning producer gas of the quality shown in Table IX, how many cubic feet of the gas would be required to produce 100 lb. of formaldehyde per hour, assuming that 40 per cent of the heating value is used for the reaction, the remainder being used in preheating and in radiation? How much methanol is required, assuming a 75 per cent yield?

Write the molecular weights of reactants and products under the equation:



$$\therefore \frac{32}{30} = 1.07 \text{ lb. CH}_3\text{OH consumed per lb. of HCHO}$$

$$100 \times 1.07 = 107 \text{ lb. of CH}_3\text{OH required at 100\% yield per hr.}$$

This is 75 per cent of the amount actually used.

$$\therefore \frac{107}{0.75} = 143 \text{ lb. of CH}_3\text{OH actually used per 100 lb. of product}$$

$$\frac{56,400}{30} = 1880 \text{ B.t.u. needed per lb. of HCHO produced}$$

$$100 \times 1880 = 188,000 \text{ B.t.u. needed per hr.}$$

Heating value of gas (net) is 128 B.t.u. per cubic foot, of which only 40 per cent is used for heat of reaction.

$$\therefore \frac{188,000}{0.40 \times 128} = 3,670 \text{ cu. ft. of producer gas needed per hr.}$$

Illustration 2.—If the bituminous coal whose analysis on an ash- and moisture-free basis as given in Table VIII was found to contain 3 per cent moisture and 7 per cent ash as received in the plant, recalculate the proximate analysis to an “as received” basis. What would be the heating value per pound of coal as received?

Consider 100 lb. of coal as received:

$$\text{Moisture} = 0.03 \times 100 = 3 \text{ lb.}$$

$$\text{Ash} = 0.07 \times 100 = 7 \text{ lb.}$$

$$\therefore 100 - (7 + 3) = 90 \text{ lb., the volatile matter and fixed carbon}$$

According to the original proximate analysis, this portion of the coal was 30.2 per cent volatile matter, 69.8 per cent fixed carbon.

$$\therefore 0.302 \times 90 = 27.2 \text{ lb. of volatile matter}$$

$$90 - 27.2 = 62.8 \text{ lb. of fixed carbon}$$

The analysis, “as received,” would therefore be:

	Per Cent
Volatile matter.....	27.2
Fixed carbon.....	62.8
Moisture.....	3.0
Ash.....	7.0
Total.....	100.0

Since 1 lb. of coal, free from ash and moisture, was shown to have a heating value of 15,500 B.t.u. and since each pound of coal as received contains 90 per cent or 0.9 lb. of heating substance, the heating value would be

$$0.90 \times 15,500 = 13,950 \text{ B.t.u. per lb. of coal as received}$$

Illustration 3.—The flue gas from a boiler plant using anthracite coal leaves the furnace at 540°F. under a pressure of 2 in. of water below atmospheric pressure. The gas, analyzed by an Orsat instrument and therefore on a “dry basis” exclusive of its moisture content, shows the following analysis:

	Per Cent
CO ₂	12.0
CO.....	1.0
O ₂	6.0
N ₂	81.0
Total.....	100.0

The coal used has 2 per cent moisture, 10 per cent ash. The air used is saturated with moisture when it enters at 80°F. Calculate:

(a) Cubic feet of dry gas, as analyzed, leaving the furnace at the given temperature and pressure per pound of carbon in the coal.

(b) Original analysis of coal as fired, assuming the sulphur and other minor items to be 3 per cent.

(c) Per cent of excess air, referred to “theoretical air” as 100 per cent.

(d) Total pounds of water leaving furnace per 100 lb. of coal as fired.

(e) Partial pressure of water vapor in flue gas as pounds per square inch and as inches of mercury.

(f) Cubic feet of wet flue gas at given temperature and pressure per ton of coal fired.

(g) Cubic feet of air entering, at 80°F. and 14.7 lb. per square inch pressure, per ton of coal fired.

(a) Basing calculations on 100 lb. mols of dry flue gas as analyzed, there are 12 lb. atoms of carbon present as carbon dioxide and 1 lb. atom of carbon as carbon monoxide, a total of 13 lb. atoms, each weighing 12 lb. Then,

$$13 \times 12 = 156 \text{ lb. of C per 100 mols dry flue gas}$$

To find the volume of gas per pound of carbon, it is then necessary to calculate the volume of the 100 lb. mols at 540°F. and at the pressure given (atmospheric — 2 in. of water). Since

$$1 \text{ atmosphere} = 33.9 \text{ ft. of water} = 14.7 \text{ lb. per sq. in.}$$

and

$$2 \text{ in. of water} = \frac{2}{12} = 0.167 \text{ ft. of water}$$

$$2 \text{ in. of water} = \frac{0.167}{33.9} \times 14.7 = 0.072 \text{ lb. per sq. in.}$$

$$\therefore \text{Pressure of flue gas} = 14.7 - 0.072 = 14.6 \text{ lb. per sq. in.}$$

For substitution in the Law of Perfect Gases, this value must be multiplied by 144, since pressure must be expressed as pounds per square foot.

$$\text{Temperature} = 540^{\circ} + 460^{\circ} = 1000^{\circ}\text{R.}$$

$$\text{Number of mols} = 100$$

$$\begin{aligned} v &= \frac{NRT}{p} \\ &= \frac{100 \times 1543 \times 1000}{14.6 \times 144} \end{aligned}$$

$$v = 73,500 \text{ cu. ft. of dry flue gas per 100 mols}$$

Since there are 156 lb. of carbon in this quantity of gas,

$$\frac{73,500}{156} = 471 \text{ cu. ft. of dry flue gas per lb. of C burned}$$

(b) To find the composition of the coal, it is necessary to determine the pounds of hydrogen associated with the carbon to form the *combustible matter*, neglecting the small amount of sulphur. Since all the hydrogen in the coal would burn to water, which would not be found in the "dry gas" as analyzed, it is evident that an oxygen balance should show a disappearance of oxygen equivalent to that used in burning the hydrogen. Neglecting the very small amount of nitrogen in the coal, it is evident that all the nitrogen in the flue gas must come in with the air in the proportion of 79.1 per cent nitrogen to 20.9 per cent oxygen or 20.9 mols of oxygen with every 79.1 mols of nitrogen. That is,

$$\frac{20.9}{79.1} = 0.264 \text{ mol of O}_2 \text{ enter per mol of N}_2$$

Since there are 81 mols of nitrogen in the 100 lb. mols of dry flue gas used as the basis of calculation,

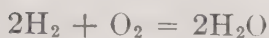
$$81 \times 0.264 = 21.4 \text{ mols of O}_2 \text{ enter per 100 mols of dry gas}$$

In the 100 mols of dry flue gas, analysis shows

12 mols of CO_2 , containing 12.0 mols of O_2
 1 mol of CO , containing 0.5 mol of O_2
 6 mols of O_2 , containing 6.0 mols of O_2
 Total 18.5 mols of O_2

$\therefore 21.4 - 18.5 = 2.9$ mols of O_2 not shown by analysis.

From the reaction for the formation of water from hydrogen, it is seen that each of these mols of oxygen burns with 2 mols of hydrogen,



$\therefore 2 \times 2.9 = 5.8$ mols of H_2 , burned per 100 mols of dry gas produced

Each mol of hydrogen weighs 2 lb.

$\therefore 2 \times 5.8 = 11.6$ lb. of H_2 burned per 100 mols of gas

Add 156. lb. of C burned per 100 mols of gas

$\therefore$ 167.6 lb. total combustible per 100 mols of dry flue gas (168 lb. for convenience)

$$\frac{11.6}{168} \times 100 = 6.9\% \text{ H}_2 \text{ in combustible}$$

$$100 - 6.9 = 93.1\% \text{ C in combustible}$$

The other components of the coal were given as,

	Per Cent
Moisture.....	2
Ash.....	10
S, etc.....	3
Total.....	<u>15</u>
Combustible is 85 %	

$$\therefore 0.069 \times 85 = 5.9\% \text{ H}_2 \text{ in coal}$$

$$85 - 5.9 = 79.1\% \text{ C in coal}$$

Calculated analysis of coal:

	Per Cent
Hydrogen.....	5.9
Carbon.....	79.1
S, etc.....	3.0
Moisture.....	2.0
Ash	<u>10.0</u>
Total.....	100.0

(c) The "theoretical air" represents the amount needed to supply enough oxygen for complete combustion of all carbon to CO_2 and all hydrogen to H_2O . Referring again to 100 mols of dry flue gas as the basis of calculation, it is seen that the CO present would require 0.5 mol of oxygen to complete its combustion to CO_2 . Deducting this from the *apparent* excess of 6.0 mols of oxygen leaves 5.5 mols of *excess oxygen*. Since 21.4 mols of oxygen enter per 100 mols of dry flue gas, the theoretical amount needed would then be

$$\begin{aligned} 21.4 - 5.5 &= 15.9 \text{ mols of } \text{O}_2 \text{ theoretically needed} \\ \therefore \frac{5.5}{15.9} \times 100 \\ &= 34.6\% \text{ excess } \text{O}_2 \text{ in entering air referred to theoretical} \end{aligned}$$

Since the mols of air are 100/20.9 times both the excess oxygen and the theoretical oxygen, it is apparent that the percentage of excess oxygen is numerically equal to the percentage of excess air.

$$\therefore \% \text{ excess air} = 34.6\%$$

(d) The total pounds of water in the outgoing flue gas must include moisture in the entering air, moisture in the coal, and moisture formed by combustion of hydrogen. The entering air is saturated at 80°F . Table III shows that the partial pressure is 0.51 lb. per square inch. The total pressure of the entering air is 14.7 lb. per square inch. Then the pressure exerted by the dry air itself is

$$14.7 - 0.51 = 14.2 \text{ lb. per sq. in.}$$

Since the mols of gas are present in any mixture in the same proportion as the partial pressures which they exert,

$$\frac{0.51}{14.2} = 0.0359 \text{ mols of } \text{H}_2\text{O} \text{ per mol dry air entering}$$

Since 21.4 mols of oxygen enter per 100 mols of dry flue gas, and since this is 20.9 per cent of the entering air,

$$\frac{21.4}{0.209} = 102 \text{ mols of dry air enter per 100 mols}$$

of dry gas leaving the furnace

$\therefore 0.0359 \times 102 = 3.66 \text{ mols of } \text{H}_2\text{O} \text{ (3.7 for convenience) enter}$
per 100 mols of dry flue gas leaving

It was calculated that 5.8 mols of hydrogen are burned per 100 mols of dry flue gas, thus producing 5.8 mols of H_2O .

$$3.7 + 5.8 = 9.5 \text{ mols of } \text{H}_2\text{O} \text{ from air and combustion}$$

$$9.5 \times 18 = 171 \text{ lb. of } \text{H}_2\text{O} \text{ from air and combustion per 100 mols of dry flue gas}$$

From the calculated coal analysis, it can be seen that there are 2 lb. of moisture associated with every 79.1 lb. of carbon. Therefore,

$$\frac{2}{79.1} = 0.0253 \text{ lb. of } \text{H}_2\text{O} \text{ per lb. of C in coal}$$

In making calculations for (a), it was found that there are 156 lb. of carbon per 100 mols of dry flue gas.

$$\therefore 156 \times 0.0253 = 3.95 \text{ lb. of } \text{H}_2\text{O} (4.0 \text{ lb.}) \text{ from moisture of coal per 100 lb. mols of dry flue gas.}$$

Then, adding the H_2O from all three sources,

$$171 + 4 = 175 \text{ lb. of } \text{H}_2\text{O} \text{ leave with 100 lb. mols of dry flue gas}$$

The problem asks for the water per 100 lb. of coal as fired. This coal corresponds to $0.791 \times 100 = 79.1$ lb. of carbon. Since the water, as calculated above, corresponds to the 156 lb. of carbon to produce 100 mols of dry gas,

$$\frac{79.1}{156} \times 175 = 88.8 \text{ lb. of } \text{H}_2\text{O} \text{ leaving per 100 lb. of coal as fired}$$

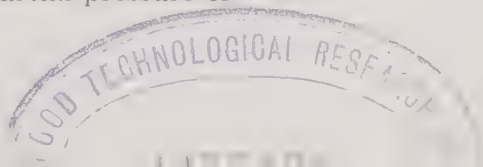
(e) To determine the partial pressure of water vapor in the flue gas leaving the furnace, determine the number of mols of water per 100 mols of dry gas. As found above, there are 175 lb. of water per 100 mols of dry gas.

$$\frac{175}{18} = 9.72 \text{ mols of } \text{H}_2\text{O} \text{ per 100 mols of dry flue gas}$$

$$100 + 9.7 = 109.7 \text{ (for convenience 110) mols of wet gas}$$

Since the total pressure of the gas was found to be 14.6 lb. per square inch and since the mol fraction is the same as the fraction of total pressure,

$$\frac{9.7}{110} \times 14.6 = 1.29 \text{ lb. per sq. in. partial pressure of water}$$



To convert this to inches of mercury, note that

$$14.7 \text{ lb. per sq. in.} = 29.9 \text{ in. of mercury}$$

$$\frac{29.9}{14.7} = 2.03 \text{ in. of mercury equivalent to 1 lb. per sq. in.}$$

$$\therefore 1.29 \times 2.03 = 2.62 \text{ in. of mercury, partial pressure of water vapor in flue gas}$$

(f) To calculate the wet gas leaving per ton of coal fired, note that the dry flue gas was found to be 471 cu. ft. per pound of carbon at the given temperature and pressure. In 2,000 lb. of coal, there are

$$0.791 \times 2,000 = 1,580 \text{ lb. of C}$$

$$\therefore 471 \times 1,580 = 745,000 \text{ cu. ft. of dry gas per ton of coal}$$

There are 110 mols of wet gas per 100 mols of dry gas.

$$\therefore \frac{110}{100} \times 745,000 = 820,000 \text{ cu. ft. of wet flue gas per ton of coal fired}$$

(g) Of the 745,000 cu. ft. of dry flue gas leaving per ton of coal burned, analysis shows that 81 per cent is nitrogen.

$$0.81 \times 745,000 = 603,000 \text{ cu. ft. of dry N}_2 \text{ at exit conditions}$$

This entered at 80°F. and 14.7 lb. per square inch pressure.

$$\therefore 603,000 \times \frac{540}{1,000} \times \frac{14.6}{14.7} = 323,000 \text{ cu. ft.}$$

of dry N₂ at inlet conditions

Since this N₂ was 79.1 per cent of the dry air entering,

$$\frac{323,000}{0.791} = 408,000 \text{ cu. ft. of dry air entering per ton of coal}$$

The partial pressure of the moisture in the entering air has been shown to be 0.51 lb. per square inch and that of the dry air itself to be 14.2 lb. per square inch. Accordingly, the cubic feet of moisture will bear the same proportion to the cubic feet of dry air as the ratio of these partial pressures.

$$\therefore \frac{0.51}{14.2} \times 408,000 = 14,700 \text{ cu. ft. of moisture in entering air}$$

$$408,000 + 14,700 = 422,700 \text{ cu. ft. (rounded off to 423,000)}$$

of wet air entering per ton of coal burned

Many of the steps in the solution as given above can be combined and shortened. However, the actual steps involved must

be clearly understood before "short cuts" are taken. It will be observed that only three significant figures have been retained in results, since the ordinary slide rule does not justify any more figures than this.

CONDENSING VAPOR AS AN ENERGY SOURCE

In a great many reactions, the energy necessary for bringing the reactants to the proper temperatures and for removing volatile products is supplied as latent heat of condensing vapors. As long as the condensing temperature of the vapor is higher than that of the charge with which it is in thermal contact (as through the metal wall of a pipe or jacket), condensation will proceed and heat will flow into the charge.

Steam is the most widely used vapor for this purpose. Accordingly, it is highly important for an operating supervisor to have a clear understanding of its properties. The most useful of these properties are conveniently arranged in steam tables (see Tables 1, 2, and 3 in the Appendix). These tables are arranged as follows:

Table 1 is based upon the temperature of vaporization and covers the range from 32°F. up to the *critical temperature*, 705.4°F., at which point the properties of liquid and of vapor coincide. For each temperature t shown in the extreme left-hand column, the *absolute pressure* at which water will boil (or steam will condense) is given as pounds per square inch. The next series of values to the right are *specific volumes* (v_f = cubic feet per pound of water at the indicated temperature, v_{fg} = increase in volume caused by evaporation of 1 lb. of water, and v_g = volume of 1 lb. of *steam* at that temperature, dry and saturated, *i.e.*, completely evaporated but with no superheating). The next series of values to the right show enthalpy, or total heat content (h_f = total heat above 32°F. contained in 1 lb. of water at the given temperature, h_{fg} = B.t.u. required to evaporate completely the pound of water, and h_g = total heat in the dry saturated steam, obtained by adding h_f to h_{fg}).

Table 2 is based upon absolute pressures in pounds per square inch, given in the extreme left-hand column. The next column to the right shows the temperature at which water boils under the indicated pressure. The other columns give corresponding values for specific volume and for heat content. The pressures range from 0.491 lb. per square inch (the vapor pressure of water

at 79.03°F.) up to the critical pressure of 3206.2 lb. per square inch.

Table 3 gives the properties of superheated steam. The heavy figures in the extreme left-hand column are absolute pressures in pounds per square inch while the lighter figures (in parentheses) show the saturation temperature, *i.e.*, the boiling point in °F. for each pressure given. The figures across the top of the table show the temperature to which 1 lb. of steam is heated at constant pressure. Under each of these temperatures are given the properties of 1 lb. of steam which has been raised to that temperature at the pressure given in the extreme left-hand column. These properties include: v = volume in cubic feet per pound of vapor, h = total heat content of 1 lb. of vapor at that pressure and temperature, and s = entropy.

When the latent heat in steam is given up to a colder body, *e.g.*, to the metal pipe of a coil carrying the steam and surrounded by material at a still lower temperature, the condensed steam must be removed to provide room for more vapor to condense. The amount of heat still contained in the condensate is relatively small so that provision is made for rapid removal of this water by means of a *trap*. This trap must be designed so that the water is discharged without any appreciable amount of "live" steam being wasted and at such frequent intervals that the heating surfaces are kept clear for condensing steam. Provision must be made, also, for correspondingly complete removal of non-condensable gases which were present in the steam, since they greatly reduce the rate of condensation on a surface.

From a study of the heat content values for saturated water, it can be seen that a pound of water which has been condensed at an elevated pressure contains appreciably more heat than a pound of water which is condensed at atmospheric pressure. Consequently, when a pound of water is discharged by a trap at the temperature at which it has condensed, the excess heat above the normal amount for atmospheric pressure causes a portion of the pound of water to evaporate ("flash") into the air.

Other vapors may be used in the same way as steam to provide energy. Thus, Dowtherm, a mixture of diphenyl and diphenyl oxide, has found increasing use in recent years because its boiling point at any given pressure is very much higher than the boiling point of water at the same pressure. One mixture (Dowtherm

"A") boils at 500°F. at atmospheric pressure and at 700°F. at 88 lb. per square inch gage pressure. This property is of great value for high-temperature operations where steam would be out of the question but where the use of a condensing vapor offers many advantages in ease of control, safety, etc. The properties of Dowtherm are given in Table 4 of the Appendix. Figure 2 shows a typical installation.

Mercury vapor, sulphur vapor, and other substances have had a limited use. Considerations such as cost, hazard from poison-

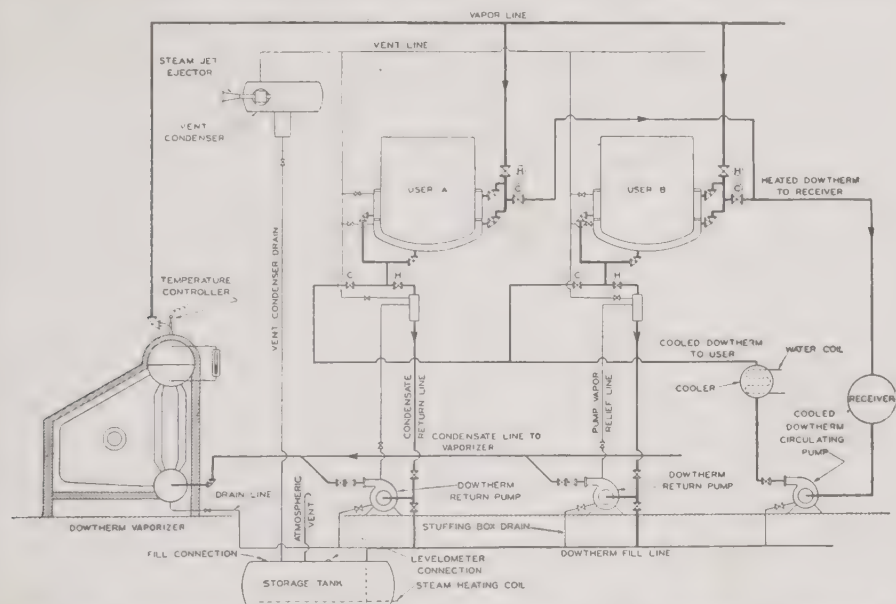


FIG. 2.—Dowtherm installation for heating and for cooling. (Courtesy of Foster Wheeler Corporation.)

ous vapors, tendency to decompose, freezing point, corrosiveness, and various other properties have to be studied for any material proposed for use as a condensing vapor for heat transfer purposes.

Heat removal, instead of heat supply, may be accomplished by the same materials as used for heat supply. Reactions liberating heat may be controlled by providing a boiling liquid to absorb their heat as fast as it is evolved. Thus, converters in which naphthalene and air react to form phthalic anhydride have been built as tubular units in which the tubes through which the reacting gases pass are surrounded by boiling mercury. The mercury vapors pass out to a condenser and the liquid mercury runs back into the space around the tubes. By adjust-

ing the pressure at which the mercury boils, its temperature is held at any desired point so that the reaction temperature inside the tubes is likewise under control.

Condensers for certain organic materials that must not cool below a certain point to prevent solidification may use boiling liquids for heat removal. For example, naphthalene stills may be provided with condensers in which water is allowed to boil around the tubes, thus preventing the condensed naphthalene from cooling below 212°F. Naphthalene freezes at about 176°F.

SENSIBLE HEAT OF GASES AS AN ENERGY SOURCE

The heat given up by gas as it cools from the temperature at which it is received into a system to the temperature at which it is discharged without any condensation of vapor is called its "sensible heat." Because of the relatively small amount of heat given up by one pound of any gas in cooling through one degree (*i.e.*, its specific heat), it is evident that large changes in temperature are necessary for any appreciable transfer of energy. The specific heats of various gases have been given previously (page 28).

All fuel-fired pieces of equipment get their energy from the cooling of the products of combustion. The efficiency of operation may be expressed as the difference between the maximum temperature of the combustion products and their minimum temperature before discharging from the system divided by the temperature at which the energy was supplied, *i.e.*, at the maximum temperature. Thus

$$\text{Efficiency} = \frac{T_{\text{max.}} - T_{\text{min.}}}{T_{\text{max.}}}$$

Although it is therefore desirable to discharge the gases at as low a temperature as possible, this is limited by the temperature of the body receiving the heat. Many processes, requiring that heat be supplied only at a relatively high temperature, are followed by waste heat recovery systems. In these, some other material that can use the heat still available in the gases at lower temperatures is provided to improve the over-all efficiency. Thus, furnace gases, cooled to a point where they can no longer supply heat to generate steam, may be used to preheat air for combustion or to heat feed water for the boilers.

Reaction gases, leaving such equipment as converters in which gas reactions are being carried out, may be passed through heat exchangers for preheating incoming feed gases on their way to the converters.

Superheated steam is sometimes used to obtain temperatures higher than are possible with the available saturated steam. The saturated steam is passed through pipes heated by direct fire and allowed to expand at substantially constant pressure.

SENSIBLE HEAT OF LIQUIDS AS AN ENERGY SOURCE

The heat given up by a liquid in cooling from its initial to its final temperature in the system, depending upon specific heat as in the case of gases, is often used to provide energy. Thus, hot water is used for close temperature control where it is undesirable to subject a material to the temperature of steam. Water is heated and circulated through the coils or jacket of the equipment. High-temperature heating has been carried out with water under very high pressures (the Frederking system), using coils cast in the walls of kettles to carry the water at pressures of several thousand pounds per square inch.

Hot oil is widely used for temperatures up to 575°F. because no pressure is involved other than that required to move the oil against the friction of the system and the hydrostatic head, because the heat can be carried to a variety of users with a relatively wide distribution, and because fire hazards are, in general, confined to the furnace in which energy from combustion gases is transferred to the circulating oil. Thermal efficiency is not high (may vary from 25 to 60 per cent) because the gases cannot be cooled so low as the incoming oil, which is usually at a temperature of 525 to 550°F. If the waste gases can be used for other purposes, the efficiency can, of course, be increased correspondingly.

The Merrill Process System of hot oil heating (Fig. 3) rates each furnace or "absorber" on the basis of the normal energy transfer per hour. Thus, a No. 12 absorber is designed to absorb 1,200,000 B.t.u. per hour in oil circulating at 130 gal. per minute through tubes heated by combustion gases from an oil-fired furnace. One oil used in the author's experience has a specific gravity of 0.910 at room temperature and 0.76 at 500°F. Its viscosity is 500 Saybolt seconds at 100°F., 58 at 210°F., and

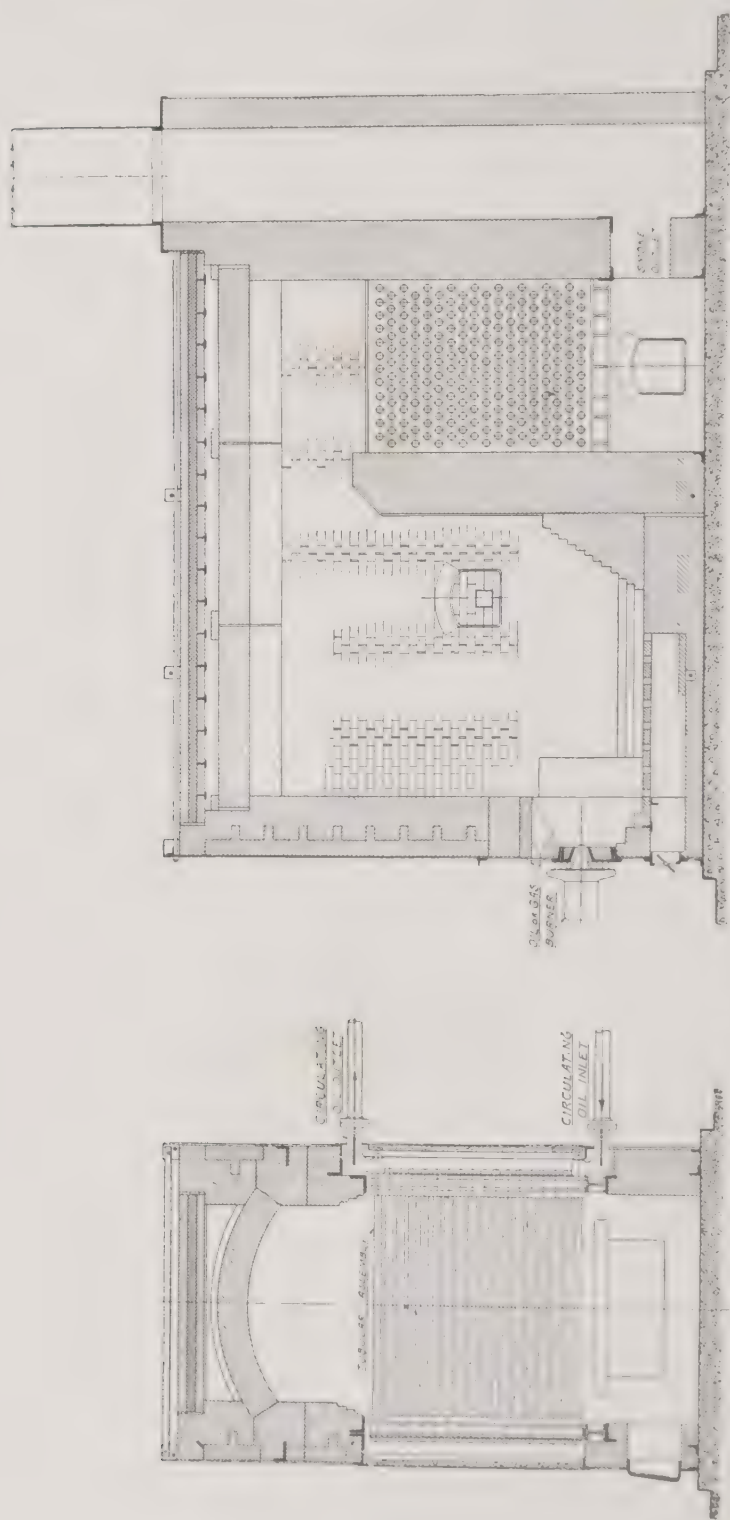


FIG. 3.—Merrill Process Absorber. (Courtesy of Parks—Cramer Company.)

20 at 500°F. The specific heat in the operating range (525 to 575°F.) may be taken as 0.635. The oil leaves the pump at a pressure of 32 lb. per square inch and enters the hot oil header from the absorber at 20 lb. per square inch. The inlet temperature varies according to the service but may be considered as 535°F.; the outlet would be about 575°F. To ensure constant feed to the pump, an overhead tank "floats" on the system, *i.e.*, is open at all times to the suction of the pump and is kept filled to a point higher than any other point in the system. This tank provides room for expansion of the oil as the system heats up and keeps all pipes full as the oil cools upon shutting down.

Difficulties in heating with circulating oil may be due to sludge or dirt in the valves or on the heating surfaces, or to noncondensable gases trapped in the jackets of kettles, etc. Periodic cleaning of heat-transfer surfaces is advisable. Vents must be provided at high points on all jackets to permit discharge of noncondensable vapors whenever they accumulate.

Molten Salt.—For temperatures above the maximum limits of oil or Dowtherm, a recent development on a large plant scale has been the use of a molten mixture of 40 per cent sodium nitrite (NaNO_2), 7 per cent sodium nitrate (NaNO_3), and 53 per cent potassium nitrate (KNO_3). This can be melted by steam at 150 lb. per square inch and can be used at temperatures up to 1000°F. at atmospheric pressure, circulated by pumping through steel piping in the same way that hot oil is handled. The specific gravity of this mixture, which is known as "HTS," varies from 1.97 to 1.68 as the temperature is increased from 300 to 1030°F. Its specific heat is given as 0.32 for the solid salt and 0.373 for the molten salt. The latent heat of fusion is 35 B.t.u. per pound. Table XIV gives a comparison of HTS with other heating mediums.

Dowtherm is used as a circulating fluid for heating in the same way as hot oil. It is especially valuable as a cooling fluid, also, when a vessel is heated by Dowtherm vapor and must then be cooled. Properties of liquid Dowtherm are shown, along with those of the vapor, in Table 4 of the Appendix.

ELECTRICAL ENERGY AS A SOURCE OF HEAT

When electricity is transformed to heat at the rate of 1,000 watts per hour, 3415 B.t.u. are liberated. By formula,

$$1 \text{ kw.-hr.} = 3415 \text{ B.t.u.}$$

This transformation is quantitative; *i.e.*, all of the electrical energy appears as heat. Methods of utilization include resistance, radiation, and induction.

Resistance—Heaters may be immersed in a fluid, such as in an oil or a salt bath, or may be clamped to the vessel to be heated, as on the bodies of kettles or stills. Sometimes a pipe line may serve as the resistor, electrical connections being made at each end of the pipe. This method has been used for melting frozen pipe lines or for keeping a material molten while flowing through the pipe. Resistance wires, insulated by "beads," are often used to maintain the temperature of pipes, distillation columns, etc.

TABLE XIV.—COMPARISON OF HEAT-TRANSFER FLUIDS*

Fluid	Usual temperature limits, °F.	Pressures, lb. per sq. in. gage
Steam or water.....	32-460	0-450
Oil.....	30-550	0
Dowtherm A.....	54-700	0-135
Mercury.....	-37-1000 or more	0-180 or more
HTS.....	290-1000	0
Flue gas or air.....	Up to 800 in iron ducts; to 1600 in special alloy ducts	

* Kirst, Nagle, and Kastner, "A New Heat Transfer Medium for High Temperatures," *Trans. Am. Inst. Chem. Engrs.*, **36**, 371 (1940).

Radiation.—Heating elements are designed so that they glow, transforming the electrical energy into radiant energy which is absorbed by the object to be heated. This method is used quite often but requires care in avoiding explosion hazards where inflammable vapors may come in contact with the glowing heaters.

Induction.—An alternating-current conductor is wound around, but not in electrical contact with, the vessel or object to be heated. The vessel, which must be of iron, steel, or nickel, forms the "core" as in an electromagnet. The passage of alternating current through the primary coil induces secondary currents in the core (*i.e.*, the shell of the vessel) and thus heat is generated. Vessels heated by this method include kettles, tunnel driers for freshly painted automobile wheels, melting pots for metal, and

various other units. The method introduces problems in power transmission lines, due to out-of-phase currents necessitating larger conductors than normal, and is limited to ferromagnetic materials.

ELECTRICAL ENERGY AS A SOURCE OF CHEMICAL ENERGY

Electrolytic Cells.—The passage of electricity through an *electrolyte* (solutions of acids, bases, and salts, fused salts, some solid substances, and hot gases) causes an actual movement of matter. Thus, if two carbon plates extending into a solution of hydrochloric acid are connected to the positive and negative terminals of a source of direct current, such as a battery, a chemical effect known as *electrolysis* takes place. At the positive *electrode*, or *anode*, chlorine gas is given off; at the negative electrode, or *cathode*, hydrogen is given off. Thus, it is evident that hydrochloric acid in solution has been decomposed, chlorine moving to the anode and passing out there and hydrogen moving to, and passing off at, the cathode. The quantities of substances set free at the electrodes are directly proportional to the quantity of electricity passing through the solution and represent the same number of chemical equivalents, regardless of the kind of electrolyte. Caustic soda is produced commercially by electrolyzing a solution of sodium chloride, chlorine gas being evolved at the anode. Instead of metallic sodium appearing at the cathode, the presence of water causes a reaction to proceed:



Thus hydrogen gas is evolved at the cathode and a solution of caustic soda flows from the cell, fresh salt solution being continually introduced at the corresponding rate.

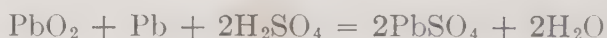
Storage Batteries.—These are electrolytic cells in which the passage of electricity from an outside source causes a chemical effect which can later be reversed by connecting the anode and cathode through an electrical conductor (user of electricity). Thus, in the common automobile battery, containing sulphuric acid as an electrolyte with lead peroxide on the cathode, charging current causes spongy lead to be deposited on the cathode while lead peroxide forms on the anode. When the battery is discharged, current flows from the anode through the external circuit (ignition, lights, etc.) and returns to the cathode and thence

completes its circuit internally through the electrolyte. During discharge, both spongy lead from the cathode and lead peroxide from the anode are dissolved in the electrolyte as lead sulphate (PbSO_4). Note that the battery stores *chemical* energy which is reconverted into *electrical* energy upon discharge. The several reactions taking place may be combined as follows:

Charging:



Discharging:



MECHANICAL ENERGY FROM ELECTRICAL ENERGY

Mechanical energy is frequently expressed in foot-pounds, 1 ft.-lb. being the energy used in lifting a weight of 1 lb. through a distance of 1 ft. *Power* is a *rate* of consuming energy or doing work, the usual measure of mechanical energy being the *horse-power*, which is defined as a conversion of energy at the rate of 550 ft.-lb. per second (33,000 per minute). If energy is converted at this rate for 1 hr., the total energy transformed is expressed as 1 horsepower-hour. It is found that 1 kilowatt hour of electrical energy equals 1.34 hp.-hr. Thus

$$1 \text{ kw.-hr.} = 1.34 \text{ hp.-hr.}$$

$$1 \text{ hp.-hr.} = 0.746 \text{ kw.-hr.}$$

$$1 \text{ hp.} = 550 \text{ ft.-lb. per sec.}$$

$$= 33,000 \text{ ft.-lb. per min.}$$

Motors.—The efficiency of conversion of electrical energy into mechanical energy by motors varies with numerous factors. However, small motors (*e.g.*, 1 to 5 hp.) deliver about 80 per cent of the input energy to the driven object, the remainder being lost in heat. On large motors (*e.g.*, 100 hp.), the efficiency may be about 90 per cent.

WORK AND HEAT FROM MECHANICAL ENERGY

Mechanical energy may be quantitatively converted into work and heat, or into heat alone. Thus

$$1 \text{ ft.-lb.} = 0.00129 \text{ B.t.u.}$$

$$1 \text{ B.t.u.} = 778 \text{ ft.-lb.}$$

$$1 \text{ hp.-hr.} = 2545 \text{ B.t.u.}$$

Efficiency.—Since all mechanical devices dissipate part of their energy as heat due to friction, only a portion of the energy delivered by the driving unit (motor, engine, etc.) appears as work. The actual work done is expressed as foot-pounds, which, divided by the input, gives the efficiency of the unit in question.

ILLUSTRATIVE PROBLEMS

Illustration 4.—After 100 lb. of water at 60°F. is pumped into a feed-water heater, the water is heated to 200°F. It is then pumped into a boiler which is operating at 190 lb. per square inch gage pressure. As saturated steam, the 100 lb. now passes to a superheater which superheats it to 500°F. Calculate the heat content of the water at each point, taking the enthalpy at 32°F. as zero.

From Table 1 of the Steam Tables in the Appendix, it is found that 1 lb. of water (saturated liquid) at 60°F. has an enthalpy of 28.06 B.t.u. per pound. Then, for the 100 lb. under consideration, letting q = heat content in B.t.u.,

$$q = 100 \times 28.1 = 2810 \text{ B.t.u.}$$

From the same table, the enthalpy of liquid water at 200°F. is 167.99 (168). Then

$$q_2 = 100 \times 168 = 16,800 \text{ B.t.u.}$$

Since the Steam Tables are based upon absolute pressure, 14.7 lb. per square inch must be added to the "gage" pressure, because an ordinary steam gage reads zero at atmospheric pressure. The pressure in the boiler in the problem, therefore, is

$$190 + 14.7 = 204.7 \text{ lb. per sq. in. absolute (205)}$$

Table 2, showing properties referred to pressure, gives values at 200 and at 250 lb. per square inch, so that the values for 205 lb. must be obtained by interpolation between these. The enthalpy of saturated liquid is found to be 358 B.t.u. per pound and that of the dry saturated vapor, 1199. Steam, superheated to 500°F., is shown to have a total heat content of 1269 B.t.u. Therefore,

$$q_3 = 100 \times 358 = 35,800 \text{ B.t.u. for liquid at 205 lb. per sq. in. (384°F.)}$$

$$q_4 = 100 \times 1199 = 119,900 \text{ B.t.u. for dry, saturated vapor at this pressure}$$

$$q_5 = 100 \times 1269 = 126,900 \text{ B.t.u. for superheated steam at } 205 \text{ lb. pressure and } 500^\circ\text{F.}$$

The heat that must be supplied for each step in the operation can be obtained by subtraction, *e.g.*, $q_5 - q_4 =$ heat required to superheat the steam, etc. In such cases, where differences of large numbers are to be taken, it is advisable to carry at least four significant figures.

Illustration 5.—One hundred pounds of steam, condensed at a pressure of 150 lb. per square inch absolute, is discharged by a trap into the air without any further cooling in the line to the trap. What percentage of the condensate will “flash” into vapor at atmospheric pressure?

From Table 2 of the Steam Tables, the heat content per pound of saturated liquid water at 150 lb. per square inch (358°F.) is 330.5 B.t.u. (331). At atmospheric pressure, 1 lb. of saturated liquid water has an enthalpy of 180.07 B.t.u. (180). Evidently, each pound of water must lose the difference between these values in order to reach equilibrium at 212°F.

$$331 - 180 = 151 \text{ B.t.u. per lb. must be given up}$$

The only way in which this heat can be given up, neglecting a small radiation to the air, is by evaporating an equivalent amount of water at 212° . From Table 1 it is noted that the enthalpy of evaporation, *i.e.*, the heat required to vaporize 1 lb. of water at 212°F. , is 970.3 B.t.u. (970). Then the total water evaporated from the 100 lb. of condensate will be

$$\frac{100 \times 151}{970} = 15.6 \text{ lb. of water “flashed off”}$$

$$\therefore \frac{15.6}{100} \times 100 = 15.6\% \text{ “flash evaporation”}$$

Illustration 6.—A Dowtherm boiler, operating at 18 lb. per square inch, gage pressure, produces 2,000 lb. of Dowtherm vapor per hour, the liquid Dowtherm being fed in at 300°F. The fuel oil used for firing the boiler has a heating value of 19,100 B.t.u. per pound and a specific gravity of 0.91. With an 80 per cent boiler efficiency, what is the fuel oil consumption in gallons per hour?

The heat content of liquid Dowtherm at 18 lb. per square inch, gage, is given in Table 4 of the Appendix as 267 B.t.u. per pound.

At 300°F., it is 108 B.t.u. per pound. The latent heat of vaporization at 18 lb. per square inch gage is given as 114 B.t.u. per pound and the total heat content of the dry, saturated vapor as 381. The heat input for each pound of liquid fed to the boiler may be calculated as heat to warm it from 300°F. to boiler temperature plus the heat to vaporize it. More simply, however, the heat content of each pound of liquid at 300°F. may be subtracted from the total heat content of the saturated vapor. Then for one hour's operation,

$$2000(381 - 108) = 2000 \times 273 = 546,000 \text{ B.t.u.}$$

This is, therefore, the heat absorbed by the boiler per hour. However, since the efficiency is 80 per cent, this value is 80 per cent of the heat in the oil used for firing.

$$\frac{546,000}{0.80} = 682,000 \text{ B.t.u., heat content of oil as fired}$$

The oil weighs $0.91 \times 8.33 = 7.58$ lb. per gallon at 19,100 B.t.u. per pound.

$$\therefore \frac{682,000}{7.58 \times 19,100} = 4.71 \text{ gal. of fuel oil per hr.}$$

Illustration 7.—The flue gas from the boiler plant discussed in Illustration 3 is used in a rotary drier, cooling from 540 to 340°F. in passing through that equipment. How many B.t.u. does the gas deliver per ton of coal fired to the boiler, assuming its specific heat to be 0.26?

From item (f) in the problem used as Illustration 3, it was found that there are 820,000 cu. ft. of wet flue gas at 540°F. and 14.6 lb. per square inch pressure, per ton of coal fired. Of this, the dry gas is 745,000 cu. ft. and the water vapor is 75,000 cu. ft. The carbon per ton of coal is 1,580 lb. and the carbon per 100 mols of dry flue gas is 156 lb.

$$\therefore \frac{1,580}{156} \times 100 = 1,010 \text{ mols of dry gas per ton of coal}$$

The mols of water vapor can be calculated from the ratio of cubic feet of water vapor to cubic feet of dry gas:

$$\frac{75,000}{745,000} \times 1,010 = 102 \text{ mols of water vapor per ton of coal}$$

$$102 \times 18 = 1836 \text{ lb. (1840) of water vapor per ton of coal}$$

From the analysis of the dry gas, the weights in the 1,010 mols can be calculated, multiplying by the respective molecular weights:

$$\begin{array}{rcl}
 0.12 \times 1,010 \times 44 & = & 5,320 \text{ lb. of CO}_2 \\
 0.01 \times 1,010 \times 28 & = & 280 \text{ lb. of CO} \\
 0.06 \times 1,010 \times 32 & = & 1,940 \text{ lb. of O}_2 \\
 0.81 \times 1,010 \times 28 & = & 22,900 \text{ lb. of N}_2 \\
 & & \hline
 & & 30,440 \text{ lb. of dry gas per ton of coal} \\
 & & 1,840 \text{ lb. of water vapor} \\
 & & \hline
 & & 32,280 \text{ lb. of wet gas (32,300)}
 \end{array}$$

The heat given up to the drier, therefore, is

$$\begin{aligned}
 32,300 \times 0.26(540^\circ - 340^\circ) &= 32,300 \times 0.26 \times 200 \\
 &= 1,680,000 \text{ B.t.u. per ton of coal}
 \end{aligned}$$

✓ **Illustration 8.**—A centrifugal pump, having an efficiency of 64 per cent, is driven by an electric motor having an efficiency of 92 per cent. The pump delivers 500 lb. of water per minute against a total head of 75 ft. What is the horsepower delivered by the motor and what is the power required by the motor?

The work accomplished is

$$\begin{aligned}
 \text{Pounds} \times \text{feet} &= \text{foot-pounds} \\
 500 \times 75 &= 37,500 \text{ ft.-lb. per min.}
 \end{aligned}$$

Since 1 hp. is 33,000 ft.-lb. per minute,

$$\frac{37,500}{33,000} = 1.14 \text{ hp.}$$

This power is 64 per cent of that delivered to the pump by the motor, and the delivered power of the motor is 92 per cent of the electrical energy that it uses.

$$\therefore \frac{1.14}{0.64} = 1.78 \text{ hp., delivered by the motor to the pump}$$

$$\frac{1.78}{0.92} = 1.93 \text{ hp., taken by the motor from the power line}$$

$$0.746 \times 1.93 = 1.44 \text{ kw. electrical power used by the motor}$$

Problems

111. A test on a boiler plant gave the following data:

Flue Gas		Air	
	Per Cent		Per Cent
CO ₂	9.5	O ₂	20.9
O ₂	9.2	N ₂	79.1
CO.....	0.3		

Temperature of flue gas, 530°F.

Pressure of flue gas, 3 in. of water above atmosphere. Calculate the actual volume of the flue gases per pound of carbon burned (neglecting moisture content of entering air), the pounds of hydrogen per pound of carbon in the fuel, and the percentage of excess air used. 65077
0.094
74% air

112. In burning limestone to produce lime, the reaction is



The atomic weight of calcium is 40.1. If 25 per cent of the heat of combustion of the coal goes up the stack and 5 per cent is lost by radiation, how many pounds of coal (heating value 14,000 B.t.u. per pound) must be used to supply the heat of reaction of 1 ton of limestone (assumed 100 per cent pure CaCO₃).

113. The flue gas from a coke-fired furnace analyzes: 10.5 per cent CO₂, 2.0 per cent CO, and 9.2 per cent O₂. If the coke, as fired, contains 3 per cent moisture and 13 per cent ash, calculate:

(a) Cubic feet of dry flue gas at 540°F. and atmospheric pressure per pound of coke fired.

(b) Percentage of excess air used.

(c) Cubic feet of dry air at standard conditions per ton of coke fired.

114. A Bessemer converter is charged with 10,000 lb. of iron containing 3 per cent carbon. How many cubic feet of air at 27°C. and 1 atmosphere are needed for the combustion of all the carbon, assuming one-third to burn to CO₂ and two-thirds to CO? What are the partial pressures of the gases evolved?

115. The gas from a pyrites burner is 7.2 per cent sulphur dioxide, 10.4 per cent oxygen, and 82.4 per cent nitrogen. Calculate:

(a) Percentage of the sulphur burned which has already been converted to sulphur trioxide (SO₃) and therefore does not show up in the gas analysis.

(b) Pounds of air admitted to the burner per pound of pyrites fired (assuming the pyrites to be 100 per cent iron disulphide (FeS₂)).

(c) Percentage of *excess* air, assuming *theoretical* air to be the amount needed to convert all the sulphur in the pyrites to SO₃.

116. A gas producer uses coke containing 1 per cent water and 13 per cent ash. The gas gives the following analysis:

	Per Cent
CO ₂	5.3
CO.....	31.8
CH ₄	0.9
H ₂	16.8
N ₂	balance

Calculate, per pound of coke consumed:

(a) Cubic feet of dry gas at standard conditions.

(b) Cubic feet of dry air at 70°F. and 1 atmosphere.

(c) Total pounds of water decomposed.

(d) Pounds of steam introduced into the producer and decomposed.

Note that this does not include any steam that passed through without reacting.

117. If the dew point of the gas leaving the producer in Prob. 116 is 100°F., calculate the steam consumption per pound of coke.

118. If the gas producer in Probs. 116 and 117 burns 2,000 lb. of coke per hour, what should be the diameter of the flue for the gas leaving at 1800°F. if the velocity at the entrance of this flue is to be 15 ft. per second?

119. The flue gas and coal analyses from a certain furnace burning powdered coal are as follows:

Flue gas:

	Per Cent
CO ₂	12.8
CO.....	1.0
O ₂	6.6
N ₂	79.6

Coal:

	Per Cent
Ash.....	10.0
Moisture.....	8.0
Combustible.....	82.0

The coal contains a negligible amount of sulphur, and the air fed to the furnace may be assumed dry.

(a) What is the percentage of excess air?

(b) Calculate per pound of coal fired:

Cubic feet of flue gas, dry, at standard conditions.

Cubic feet of flue gas, actual, at 572°F.

Cubic feet of air used, dry, standard conditions.

120. In the reaction to produce hydrochloric acid by the combustion of hydrogen and chlorine, how much heat would be evolved per 1,000 cu. ft. of hydrogen burned?

121. The heat for carrying out the conversion of 100 lb. of ethanol per hour to ethylene is to be supplied by burning producer gas. If the thermal efficiency of the process is 60 per cent, how many cubic feet of gas at 70°F. and 1 atmosphere pressure would be required?

122. A fuel oil, analyzing 84.0 per cent C, 12.7 per cent H, 1.2 per cent O, 0.4 per cent S, and 1.7 per cent N, is burned with 50 per cent excess air. If all carbon burns to CO₂, what is the analysis of the resulting flue gas, neglecting S and N content of the fuel?

123. Owing to a leak, 4 lb. of hydrogen escapes into a room 20 ft. wide, 30 ft. long, and 20 ft. high. If a motor sparks in this room, would you expect an explosion to occur?

124. If 4 lb. of benzene vapor (C_6H_6) leaked into the room instead of hydrogen, would the danger of explosion be greater or less?

125. If the contents of a 750 cu. ft. tank containing 28 lb. of carbon monoxide and 29 lb. of air at a pressure of 1 atmosphere are being pumped through a 12-in.-diameter pipe in 10 min., and the flame from a welder's torch ignites the gas at the discharge end of the pipe, will the flame travel back through the pipe to the tank?

126. If the tank in Prob. 125 had contained 28 lb. of methane and 29 lb. of air, which were being pumped under the same conditions, would a flame travel back?

127. Estimate the heating value of 1,000 cu. ft. of a gas made up of air with the theoretical amount of a natural gas containing 32 per cent methane (CH_4), 65 per cent ethane (C_2H_6), and 3 per cent nitrogen if the heating value of the pure gas is 1200 B.t.u. per cubic foot at standard conditions.

128. If a boiler produces 40,000 lb. of saturated steam per hour at a pressure of 125 lb. per square inch gage with feed water entering at $170^\circ F.$; how much heat is utilized per hour? How many tons of coal would be burned per 24 hr. if the boiler efficiency is 75 per cent and the heating value of the coal, as fired, is 13,500 B.t.u. per pound?

129. What is the rating of the above boiler in boiler horsepower? Note that a boiler horsepower is the absorption of an amount of heat equivalent to the evaporation of 34.5 lb. of water per hour from and at $212^\circ F.$ Use heat values given in the Steam Tables.

130. A certain boiler produces 80,000 lb. of steam per hour at a pressure of 400 lb. per square inch absolute and at a temperature of $600^\circ F.$ If the feed water enters at $212^\circ F.$, how much heat is used in heating the water to boiling, how much for evaporation, and how much for superheating?

131. The average temperature of the products of combustion sweeping past a superheater is reduced from 1000 to $800^\circ F.$ If 12 lb. of gas is produced by each pound of fuel, how many pounds of steam are superheated from saturation to a final temperature of $600^\circ F.$ for each pound of fuel burned? Steam pressure is 145 lb. gage. Neglect all losses. Take the specific heat of combustion gases as 0.24.

132. For the steam produced in the boiler described in Prob. 128, the main is designed for a velocity of 5,000 ft. per minute. What is its diameter?

133. If the superheated steam produced as in Prob. 130 is to be conveyed at a velocity of 8,000 ft. per minute through two pipes, one of which carries 80 per cent of the total steam, calculate the size of each pipe.

134. A certain still uses 1,000 lb. of steam per hour at 125 lb. per square inch gage pressure. If the condensate discharges from a trap without cooling below the temperature at which is condensed, how many pounds of condensate flash into vapor per hour, if the atmospheric pressure is 14.7 lb. per square inch?

135. In a Dowtherm boiler, 5 gal. of fuel oil is burned per hour, with an efficiency of 70 per cent. The specific gravity of the oil is 0.940 and its

heating value is 18,500 B.t.u. per pound. If the Dowtherm condensed in the system returns to the boiler at 250°F. and the boiler operates at 12 lb. per square inch gage pressure, how many pounds of Dowtherm vapor are produced per hour?

136. To supply the same heat to a process by circulating hot oil as by condensing the Dowtherm produced in Prob. 135, how many gallons of oil must be circulated through equipment, entering the jackets at 570°F. and leaving at 540°F.? Take characteristics of circulating oil as given in notes on the Merrill Process System.

137. For a distillation at 400°F., heat is to be supplied by circulating liquid Dowtherm, entering the heating unit of the still at 450°F. and leaving at 420°F. Ten per cent of the heat supplied is lost by radiation. If 500 lb. of the liquid is distilled per hour, the latent heat being 200 B.t.u. per pound, what is the capacity of the Dowtherm circulating pump in gallons per minute?

138. The latent heat of vaporization of naphthalene is 136 B.t.u. per pound. If 750 lb. per hour is to be condensed by means of water boiling at atmospheric pressure around the condenser tubes, how many gallons per hour of water at 70°F. must be fed to the condenser?

139. A mixture containing 75 per cent ammonia and 25 per cent air, by volume, bubbles through an organic liquid having a vapor pressure of 4.9 lb. per square inch at the temperature (80°C.) at which it is held. The molecular weight of this material is 56. The average specific heat of the resultant gas mixture is 0.6. The gaseous mixture is then heated to 1500°F. by means of heat exchange from hot combustion gases leaving the process at 2000°F. and cooling in the exchanger to 1600°F., the specific heat of these waste gases being 0.24. If 85 lb. of ammonia is handled per hour, how many pounds of combustion gases pass through the heat exchanger per hour?

140. For a certain reaction, heat must be supplied by superheated steam at 20 lb. per square inch absolute, cooling from 500 to 300°F. If 20,000 B.t.u. per hour are required by the process, how many pounds of steam pass through the unit, assuming 15 per cent loss by radiation? Using saturated steam at 300°F. to deliver the same heat, assuming the same percentage of loss, how many pounds of steam would be required?

141. A 25-gal. still is heated by twenty 1-kw. heaters clamped along the lower third of the horizontal shell. If 30 per cent of the heat is lost by radiation, how many pounds of benzene can be evaporated per hour?

142. If the still in Prob. 141 is also provided with an internal steam coil, how many pounds of steam at atmospheric pressure would be used per hour for the same amount of distillation, assuming 10 per cent heat loss? If the steam costs 40 cents per 1,000 lb. and the electricity 1.5 cents per kilowatt-hour, what is the total cost per hour in each case?

✓ **143.** Thirty gallons of oil per hour, similar to the circulating oil of the Merrill Process System, is to be heated by an electric immersion heater from 60 to 200°F. Take the specific heat of the oil at 0.6. What is the consumption of electricity, assuming 5 per cent heat loss?

✓ **144.** A centrifugal pump, having an efficiency of 40 per cent, delivers 50 gal. per minute of water against a total head of 60 ft. What is the horsepower of the motor required?

- ✓ **145.** If a 10-hp. motor, having an efficiency of 85 per cent at full load, is connected to a rotary pump whose efficiency is 90 per cent, how many pounds of oil (sp. gr. 0.910) can be pumped per hour to a tank on the roof of an adjacent building, 50 ft. above the pump, assuming no friction loss in the pipe?
- ✓ **146.** An agitator motor uses 7.46 kw. of electric power. If 50 per cent of this is lost as friction outside of the vessel, what rise in temperature of 3,000 lb. of water in the tank would be produced in 1 hr. if the tank is at 60°F. initially and there are no heat losses?
- 147.** If a boiler plant makes steam at 185 lb. per square inch gage pressure at an over-all efficiency of 80 per cent, using coal having a heating value of 14,000 B.t.u. per pound, and the resultant steam is used to generate electricity at the rate of 1 kw.-hr. per 70 lb. of steam, what is the over-all efficiency from coal to B.t.u. produced by converting the electricity into heat? Assume that the feed water enters at 160°F.
- ✓ **148.** If a 0.5-hp. motor has an efficiency of 80 per cent, how many watts will it use?
- ✓ **149.** If the motor is used to drive a pump that is 75 per cent efficient, how many pounds of sulphuric acid (sp. gr. 1.84) will it deliver per minute against a head of 15 ft.?
- ✓ **150.** The heat evolved in the combustion of 5 lb. of coal was sufficient to raise the temperature of 2,500 lb. of water from 17 to 30°C. The heat evolved in the combustion of 1,000 lb. of this fuel would be equivalent to how many foot-pounds of work?

CHAPTER III

HEAT TRANSFER

The preceding chapters have discussed some of the fundamental principles relating to matter and energy and have illustrated ways in which these principles are used in solving plant problems. The remainder of the book will discuss five of the most important "unit operations" of chemical engineering, so-called because most chemical plant procedures can be broken down into these and a few other such units. Of the five selected as especially useful for quantitative treatment here, heat transfer is the most universal, entering into the conduct of practically every plant process.

The fundamental basis for calculating the flow of heat is Newton's law, which states that *the quantity of heat flowing in a given time through a given section of material at right angles to the direction of flow is directly proportional to the difference in temperature between the two sides of this section and to the area through which the heat flows, and is inversely proportional to the thickness of the section.* Since the transfer of heat is of primary importance in the majority of chemical engineering operations, the applications of this law to many varieties of practical problems have been studied extensively and still constitute the chief interest of many investigators. In the present book, interest lies in the operation rather than in the design of equipment, so that most attention will be given to the factors that influence the control of existing heat-transfer apparatus.

Since heat flows because of a driving force (temperature difference) against the resistance offered by the conducting material, the law may be expressed as

$$q = \frac{\Delta t}{R} \quad (1)$$

In this equation, q is expressed as B.t.u. per hour, Δt as temperature difference in degrees Fahrenheit, and R as resistance in "thermal ohms." In this form, it is evident that the flow of

heat is similar to the flow of electricity, in which

$$I = \frac{E}{R}$$

where I = current in amperes, E = potential difference in volts, and R = resistance in ohms.

Methods of Heat Transfer.—Three methods for transfer of heat are recognized:

(a) *Conduction.*—Energy may flow through a conducting body by transfer from one molecule to the next, without visible movement of the body, as, for example, through an iron bar which is hotter at one end than at the other.

(b) *Convection.*—Energy may be carried by movement of heated fluids away from a hot body, as in the heating of water by a hot surface. In this case, each particle of water moves away with some heat and another takes its place.

(c) *Radiation.*—Energy may be transmitted from a hot to a cold body by “electromagnetic” waves, this energy being converted to heat when absorbed by the other body.

Transfer by Conduction.—Instead of using equation (1), it is customary to express heat flow by conduction as

$$q = \frac{kA \Delta t}{L} \quad (2)$$

In this case, A is the cross-sectional area of the conductor in square feet. Δt is temperature difference in degrees Fahrenheit, L is length of conductor in feet, and k is the “coefficient of conductivity” expressed as the B.t.u. that will flow in 1 hr. through a conductor 1 ft. long and 1 sq. ft. in cross section, when there is a temperature difference of 1°F. from one end of the conductor to the other. This coefficient is a characteristic of the material of which the conductor is made and varies with temperature. Table XV shows coefficients for some materials in common use.

In the case of conductors that have the same cross section throughout the length under consideration (*e.g.*, flow from one end of a metal bar to the other end), the quantity of heat flowing per hour is calculated by equation (2). However, in some cases, the area is continually increasing or decreasing. For example, heat loss from an insulated pipe takes place radially from the metal surface through a constantly increasing area until it reaches

the maximum area of the surface of the insulation. On the other hand, heat flow from a room into cold brine flowing inside a pipe covered with cork or hair felt, starts with a large outside surface and passes radially inward through a constantly decreasing area

TABLE XV.—COEFFICIENTS OF THERMAL CONDUCTIVITY*

Material	k at 212°F.	k at 32°F.
Metals:		
Aluminum.....	119	117
Brass.....	60	56
Copper.....	218	224
Wrought iron.....	32	
Lead.....	20	20
Nickel.....	34	36
Silver.....	238	242
Steel.....	26	
Nonmetals:		
Boiler scale.....	0.5–1.5	
Glass.....	0.3–0.6	
Magnesia.....	0.04	
Asbestos.....	0.12	0.087
Cork.....	0.03	
Pine wood, along fibers...	0.2 at 70°F.	
Pine wood, across fibers..	0.1 at 59°F.	
Brick-Penna. fire brick...	1.0 at 2300°F.	
Brick-carborundum.....	5.6 at 1800°F.	
Brick Sil-O-Cel.....	0.03 at 1800°F.	
Gases:		
Air.....	0.0165	0.0129
Steam.....	0.0126	
Liquids:		
Water.....	0.372 at 167°F.	0.347 at 86°F.
Lubricating oil.....		0.08 at 86°F.

* Selected from the extensive tables, pp. 694–697, in "Principles of Chemical Engineering," by Walker, Lewis, McAdams, and Gilliland, McGraw-Hill Book Company, Inc., New York, 1937.

until it reaches the pipe. In either case, the term A in equation (2) must be expressed as $A_{\text{ave.}}$, the average area of the section.

Generally, the average area for cases such as those noted above is taken as the *arithmetic mean* of the largest and smallest area traversed. Thus, representing the maximum and minimum areas as A_1 and A_2 ,

$$A_{\text{ave.}} = \frac{A_1 + A_2}{2} \quad (3)$$

In the relatively few cases in which the maximum area is very large in comparison with the minimum (*e.g.*, over twice as great) a considerable error is introduced in using the arithmetic mean as the average area. It is then necessary to use the *logarithmic mean*.

$$A_{\log \text{ ave.}} = \frac{A_1 - A_2}{2.3_{\log_{10}} \frac{A_1}{A_2}} \quad (4)$$

When heat flows through several conductors in series, it is convenient to add the resistances of all the conductors and then use the resistance type of formula. For any conductor,

$$q = \frac{\Delta t}{R} \quad \text{and} \quad R = \frac{L}{kA} \quad (5)$$

using the units already given for these symbols. Thus

$$R_1 = \frac{L_1}{k_1 A_1}$$

$$R_2 = \frac{L_2}{k_2 A_2}$$

$$R_3 = \frac{L_3}{k_3 A_3}$$

Then the total resistance $R = R_1 + R_2 + R_3$ and the heat transferred through the entire series is

$$q = \frac{\Delta t}{R} = \frac{\Delta t}{R_1 + R_2 + R_3} \quad (6)$$

Note that Δt is the temperature difference between the extreme ends of the entire series in this case.

To reduce heat loss from a hot furnace, kettle, etc., materials of low conductivity (*e.g.*, magnesia) are used to cover or "insulate" the hot surfaces. In view of its very low conductivity, air would make an ideal insulator if convection could be prevented. This is actually accomplished by using highly porous materials containing a multiplicity of tiny particles of air, as in 85 per cent magnesia block.

ILLUSTRATIVE PROBLEMS

Illustration 1.—What quantity of heat will flow per hour through a brick and mortar wall 9 in. thick if the coefficient of

conductivity k has been determined as 0.4 and the wall is 10 ft. high by 6 ft. wide, the temperature on one surface being 330°F. and on the other, 130°F. ?

By equation (2),

$$q = \frac{kA \Delta t}{L}$$

Of these values, k has been given as 0.4 B.t.u. per hour per square foot of area per foot of thickness; A , the area, is

$$6 \text{ by } 10 \text{ ft.} = 60 \text{ sq. ft.};$$

Δt , the temperature difference between the hottest side and the coldest side, is $330^{\circ} - 130^{\circ} = 200^{\circ}$; L , the length of the path along which the heat travels is 9 in. = 0.75 ft.

$$q = \frac{0.4 \times 60 \times 200}{0.75} \\ = 6400 \text{ B.t.u. per hr.}$$

Illustration 2.—A pipe, whose outside diameter is $2\frac{1}{2}$ in., is insulated with a 2-in. layer of asbestos ($k = 0.12$), followed by a $1\frac{1}{2}$ -in. layer of cork ($k = 0.03$). If the temperature of the outer surface of the pipe is 290°F. and that of the outer surface of the cork is 90°F. , calculate:

- (a) Heat loss per hour per 100 linear feet of pipe.
- (b) Temperature at the interface of asbestos and cork.
- (c) Percentage of total resistance due to asbestos and to cork.

(a) Since this problem involves an over-all temperature difference and a series of two resistances, it should be solved by equation (6), which becomes

$$q = \frac{\Delta t}{R} = \frac{\Delta t}{R_1 + R_2}$$

The areas are increasing radially, so that the average area must be calculated for the asbestos and for the cork. Each area = $\pi \times \text{diameter in feet} \times \text{length of cylinder}$.

$$\therefore 3.14 \times \frac{2.5}{12} \times 100 = 65.4 \text{ sq. ft., inside surface of asbestos}$$

Since each of the other areas is to this area as its diameter is to

this diameter, and $D_2 = 2.5 + 2 \times 2 = 6.5$ in., outside asbestos,

$$65.4 \times \frac{6.5}{2.5} = 171 \text{ sq. ft.},$$

outside surface of asbestos and inside of cork

Then $D_3 = 6.5 + 2 \times 1.5 = 9.5$ in., outside cork.

$$65.4 \times \frac{9.5}{2.5} = 249 \text{ sq. ft.}, \text{ outside surface of cork}$$

For the asbestos, the average area is

$$A_{1\text{ave.}} = \frac{65.4 + 171}{2} = 118 \text{ sq. ft.}$$

For the cork, the average area is

$$A_{2\text{ave.}} = \frac{171 + 249}{2} = 210 \text{ sq. ft.}$$

The distance through the asbestos is $L_1 = \frac{2}{12} = 0.167$ ft. Then

$$R_1 = \frac{L_1}{k_1 A_{1\text{ave.}}} = \frac{0.167}{0.12 \times 118} = 0.0118 \text{ thermal ohm}$$

The distance through the cork is $L_2 = \frac{1.5}{12} = 0.125$ ft.

$$R_2 = \frac{L_2}{k_2 A_{2\text{ave.}}} = \frac{0.125}{0.03 \times 210} = 0.0198 \text{ thermal ohm}$$

Since $\Delta t = 290^\circ - 90^\circ = 200^\circ\text{F.}$,

$$q = \frac{200}{0.0118 + 0.0198} = \frac{200}{0.0316} = 6330 \text{ B.t.u. per hr. per 100 ft. of pipe}$$

(b and c) To find the temperature at the interface, when Δt is the unknown, $q = 6330$, and $R_1 = 0.0118$ thermal ohm.

$$\therefore \Delta t = q R_1 = 6330 \times 0.0118 = 74.7^\circ\text{F.}$$

$290^\circ - 74.7^\circ = 215.3^\circ\text{F.}$, temperature at interface

$$\frac{100 R_1}{R_1 + R_2} = \frac{0.0118}{0.0316} \times 100$$

$= 37.3\%$ of resistance due to asbestos

$100 - 37.3 = 62.7\%$ of resistance due to cork

Transfer by Convection.—Convection, the transfer of heat by movement of heated particles of fluid away from the hot body

and their continual replacement by colder particles, does not, of course, apply to transfer through solids. It is, however, of controlling importance in most cases of transfer between solids and fluids (liquids or gases). Although there are a great many factors that influence the rate at which heat flows by convection to or from a solid in contact with a hotter or colder fluid, the most important of these is the observation that there is always a very thin film of practically stationary fluid on the surface of the solid. Through this film, heat must flow by conduction. As shown by Table XV, the value of k for liquids is quite low and for gases is exceedingly low. In the main body of the fluid, heated particles move freely and rapidly but since the particles of the film are substantially stationary, the film always offers the major resistance between the solid and the main body of fluid. Consequently, efforts to improve heat transfer by convection are always directed toward reducing the thickness of the highly insulating film, *e.g.*, by increased velocity of the moving fluid.

Since the thickness of the fluid film on a solid is unknown and variable and since the conductivity of most liquids is likewise unknown, it is not practicable to use the heat-transfer equation in the form given in equation (2). Instead, for calculating heat transferred by convection, the flow is expressed as

$$q = h_c A \Delta t \quad (7)$$

As before, q is the B.t.u. per hour, Δt is the difference in temperature in degrees Fahrenheit between the solid and the main body of the fluid, A is the area of solid surface in square feet, and h_c is the surface coefficient for convection. Its value is expressed as B.t.u. transferred per hour by 1 sq. ft. of surface when there is a difference of 1°F. between the temperature of the solid and that of the main body of fluid. The coefficient, h_c , has been studied for many fluids under a variety of conditions, and the results are expressed in equations of varying degrees of complexity. Some of the simpler expressions are as follows:

(a) From *solid surface to still air*, natural convection:

$$h_c = 0.7 + \frac{\Delta t}{375} \text{ for values of } \Delta t \text{ from 10 to } 500^\circ\text{F.} \quad (8)$$

For convection upward from horizontal walls, increase the value of h_c by 10 per cent. For convection downward from horizontal walls, decrease h_c by 50 per cent.

(b) For *gases flowing in turbulent motion* inside pipes or in annular spaces:

$$h_c = \frac{0.22C_p T^{2.5} G^{0.8}}{D^{0.2}} \quad (9)$$

In this formula C_p is the specific heat of gas, T is the temperature of the film in degrees Rankine, G is the mass velocity of gas flow in pounds per second per square foot of cross-sectional area of gas stream, and D is the diameter of the conduit in inches.

(c) From *solids to liquids which are not boiling*: For water with natural circulation, h_c varies from 50 to 300, and for more viscous liquids it varies from 10 to 50. These large variations are due to differences in the thermal conductivity and viscosity of the liquid, shape of the vessel, etc. For *turbulent flow of water*, pumped through smooth pipes:

$$h_c = \frac{200}{D^{0.2}} \left(\frac{u}{z} \right)^{0.8} \quad (10)$$

In this case, u is the linear velocity of the water in feet per second, z is the viscosity of the water relative to that at 68°F., and D is the inside diameter of the pipe in inches.

(d) From *solids to boiling liquids*: h_c varies from 200 to 4,000, depending on the viscosity and density of the liquid, the velocity of the liquid past the surface, the arrangement of the heating surface, etc. In general, values are higher when Δt is higher.

(e) From *condensing vapors to solids*: For condensing steam, practically free from air, $h_c = 2,000$. According to one investigator, the presence of 10 per cent of air in the steam will cut this value to 1,000. For other condensing vapors, the coefficient varies with the thermal conductivity of the liquid film and with its viscosity. For carbon tetrachloride, h_c has been given as 280; for benzene, 370; and for Dowtherm, 400.

ILLUSTRATIVE PROBLEMS

Illustration 3.—A metal wall in contact with condensing steam at 10 lb. per square inch gage pressure is at a temperature of 238°F. How much heat is transferred per hour to 10 sq. ft. of the metal surface?

The steam is at $10 + 14.7 = 24.7$ lb. per square inch, absolute. According to the Steam Tables, the temperature would be

240°F. Then

$$\Delta t = 240^\circ - 238^\circ = 2^\circ\text{F.}, \quad A = 10 \text{ sq. ft.}, \quad h_c = 2,000$$

$$q = h_c A \Delta t$$

$$= 2,000 \times 10 \times 2 = 40,000 \text{ B.t.u. per hr.}$$

Illustration 4.—An insulated tank, 4 ft. in diameter by 6 ft. high, is supported on legs so that air can circulate around it. The surface of the lagging is said to be at a temperature of 40°C. Calculate the heat loss by convection to a room at 50°F.

The area of the flat top is $\pi D^2/4$, where D = diameter in feet.

$$A_{\text{top}} = 0.785 \times 4^2 = 0.785 \times 16 = 12.6 \text{ sq. ft.}$$

The area of the cylindrical sides is πDh , where h = height in feet.

$$A_{\text{sides}} = 3.14 \times 4 \times 6 = 75.4 \text{ sq. ft.}$$

Using equation (8),

$$h_c = 0.7 + \frac{\Delta t}{375}$$

$$\Delta t = (40 \times 1.8 + 32)^\circ - 50^\circ = 104^\circ - 50^\circ = 54^\circ\text{F.}$$

$$\therefore h_c = 0.7 + \frac{54}{375} = 0.7 + 0.144 = 0.844 \text{ B.t.u./hr./sq. ft./}^\circ\text{F.}$$

For the sides,

$$q = 0.844 \times 75.4 \times 54 = 3440 \text{ B.t.u. per hr.}$$

For the top, increasing normal value by 10 per cent,

$$q = 0.844 \times 12.6 \times 54 \times 1.1 = 632 \text{ B.t.u. per hr.}$$

For the bottom, decreasing normal value by 50 per cent,

$$q = 0.844 \times 12.6 \times 54 \times 0.50 = 287 \text{ B.t.u. per hr.}$$

$$\text{Total loss} = 3440 + 632 + 287 = 4359 \text{ B.t.u. per hr. (4360)}$$

Transfer by Radiation.—The transfer of radiant energy can be considered from the standpoint of light, although it is understood that visible light represents only that portion of the total energy to which our eyes are sensitive. Every object radiates energy in proportion to its absolute temperature and to its emissivity.

Objects receiving radiation may absorb, reflect, and transmit varying proportions of the energy, just as visible light is absorbed

by a black cloth, reflected by a highly polished mirror, or transmitted by a transparent window. Most objects with which we are concerned are opaque, so that absorption and reflection are the major considerations. An object that can absorb all the radiations striking it and reflect none is called 100 per cent "black" and any object reflecting part of the radiant energy without absorption is classified as 20 per cent black, 80 per cent black, etc., according as it absorbs 20 per cent or 80 per cent of the energy coming to it.

The ability of a solid to *radiate* energy is likewise dependent upon the same property of "blackness," so that a body which is 75 per cent "black" as an absorber of radiant energy will radiate from itself only 75 per cent as much energy as a 100 per cent black body would send out at the same temperature. This fraction is called its "per cent emissivity." Highly polished metals have low emissivities and are correspondingly good reflectors of heat (and light) but are poor radiators. Most nonmetals are over 80 per cent "black" at moderate temperatures. With increasingly high temperatures, nearly all substances show increased emissivity or "blackness." The effect of type of material, condition of the surface, and temperature upon the per cent emissivity e is illustrated by the examples in Table XVI.

Since every object that can "see" other objects is radiating to them at a rate corresponding to its temperature and emissivity and is at the same time receiving radiant energy from them at a rate corresponding to its area and absorptive power ("blackness") and to their temperature and emissivity, the net heat obtained per hour is the difference between what the body receives and what it radiates. This net heat interchange is expressed as a formula for two surfaces that "see" each other:

$$q = 0.173A \left[\left(\frac{T_1}{100} \right)^4 - \left(\frac{T_2}{100} \right)^4 \right] F_A F_E \quad (11)$$

In this case, q is the net rate of heat radiation in B.t.u. per hour, A is the area in square feet of whichever surface is being considered, F_A is a factor for the average angle throughout which the surface under consideration "sees" the other, and F_E is a factor that takes care of the relative "blackness" of the two surfaces. The temperatures of the surfaces (T_1 and T_2) are expressed in

degrees Rankine. The fact that the value q is proportional to the difference of the fourth powers of the absolute temperatures explains the very great increase in radiant energy interchange by rather small increases in the hot body temperature, if that temperature is already high.

TABLE XVI.—COMPARISON OF EMISSIVITIES OF VARIOUS MATERIALS*

Surface	Temperature, °F.	Emissivity (e), %
Aluminum:		
Highly polished plate.....	440	3.9
	1070	5.7
Oxidized at 110°F.....	390	11.0
	1110	19.0
Brass:		
Highly polished.....	476	2.8
	674	3.1
Dull.....	120–660	22.0
Copper:		
Highly polished.....	176	1.8
Heavily oxidized.....		78.0
Iron:		
Highly polished.....	800	14.4
	1880	37.7
Oxidized.....	212	73.6
Rough steel plate.....	100	94.0
	700	97.0
Nickel:		
Polished.....	68	4.5
Polished + 0.001 in. oil.....	68	27.0
Brick (rough, red).....	70	93.0
Paint, etc.:		
Snow-white enamel on rough iron plate...	73	91.0
Black, shiny lacquer on iron.....	76	87.5
Oil paints, all colors.....	212	92–96
Aluminum (10 % Al).....	212	52.0
Aluminum (26 % Al).....	212	30.0

* These values were selected from the extensive table by H. C. Hottel in "Chemical Engineer's Handbook," 2d ed., pp. 1004–1007, ed. by J. H. Perry, McGraw-Hill Book Company, Inc., New York, 1941.

For convenience, the radiation from a relatively small black body to a room can be expressed as a surface coefficient h_r and used in a formula of the same sort as for convection calculations.

Then,

$$q = h_r A \Delta t \quad (12)$$

In this case, q is the net heat radiated per hour from the hot object (kettle, steam pipe, etc.), A is the area of the hot surface in square feet, Δt is the temperature difference in degrees Fahren-

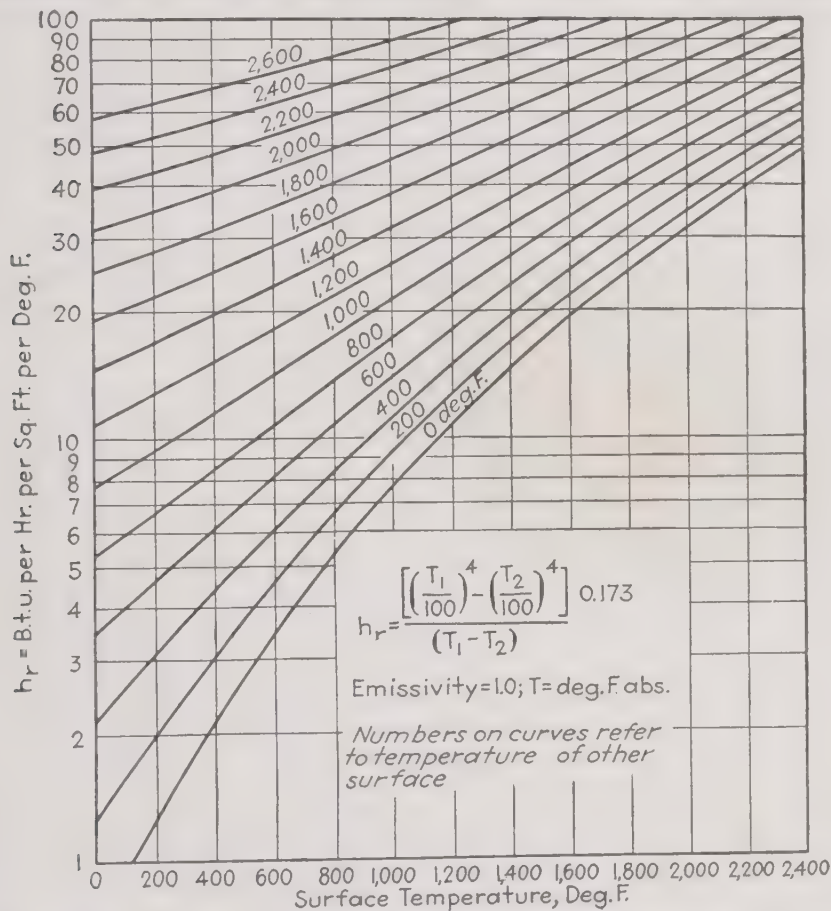


FIG. 4.—Surface coefficients of radiation, h_r , for various temperatures. (Walker, Lewis, McAdams and Gilliland.)

heit between the object and the room, and h_r is the surface coefficient of radiation. Its value, numerically, is in B.t.u. radiated per hour per square foot of hot surface, when the temperature difference between the surface and the room is 1°F . The value is calculated on the assumption that the hot body is 100 per cent black, so that values obtained must be multiplied by e , the per cent blackness of the object. Table XVII gives values¹ of h_r

¹ For more complete data, see Fig. 4.

for various temperatures of hot surfaces when the room is at 0°F. and at 70°F.

TABLE XVII.—SURFACE COEFFICIENT OF RADIATION

Temperature of body, °F.	Value of h_r for 100 % black body	
	In room at 0°F.	In room at 70°F.
100	0.9	1.5
200	1.2	1.6
300	1.6	1.9
400	2.1	2.4
500	2.8	3.1
600	3.5	3.9

Applications.—For our purposes, the relative blackness of various materials is of interest from the standpoint of increasing heat removal by radiation from hot surfaces and of decreasing heat absorption by objects that should be kept cool. The advantage of aluminum paint over other paints on solvent storage tanks for decreasing the absorption of heat from sunlight will be evident. Conversely, the advantages of other kinds of surfaces where cooling by radiation is desired will be apparent.

Transfer by Combinations of Methods.—In most problems we have heat transferred by more than one of the three methods, frequently by all three. Thus, in the case of an insulated steam pipe, heat flows by convection and conduction through the gas film on the inside of the pipe, by conduction through the metal of the pipe, by conduction through the increasing area of the insulating material, and finally by convection and radiation from the outside of the pipe. In the case of heat loss from a furnace, heat flows into the inner wall of the furnace by radiation and convection from the burning fuel, through the several layers of brick by conduction, and from the outside of the walls by radiation and convection. Likewise, in the case of a steam coil in a kettle, heat flows by conduction and convection through the steam and water films on the inside of the pipe, by conduction through the metal of the pipe, and by convection from the outer surface through the liquid film into the main body of liquid.

The most exact method of calculating a combination of transfers like those noted above is to calculate each step separately.

Since the individual temperatures at each "boundary" are generally unknown, only the over-all Δt being given (*e.g.*, condensing steam to room), it is necessary to make a preliminary assumption of each boundary temperature, calculate the flow through each section in the series, and then compare the various values of q obtained. Since the value of q (heat flowing per hour) *must* be the same through each section, any value of q that comes out higher than the others indicates that too great a temperature

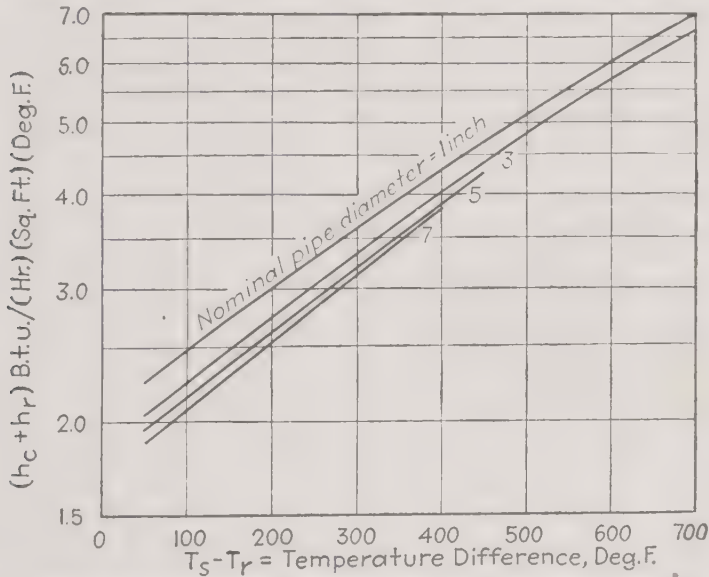


FIG. 5.—Combined coefficients, for heat transfer by radiation, conduction, and natural convection from bare steel pipes to surroundings at room temperature. (Walker, Lewis, McAdams and Gilliland.)

drop was assumed for that section. New values for the various temperatures are then chosen and new calculations made until a balance is reached.

For cases where heat loss from a surface (*e.g.*, steam pipe or outside of kettle insulation) to a room is to be calculated, the temperature of this surface may often be measured or estimated closely enough. It is then possible to add the coefficients for convection (h_c) and for radiation (h_r) and use the formula,

$$q = (h_c + h_r) A \Delta t \quad (13)$$

For heat losses from bare pipes Fig. 5 gives values of $(h_c + h_r)$ for values of Δt from 50 to 700°F.

In many cases, where the more accurate but more laborious method of stepwise calculation is not feasible, it is customary to

use an "over-all coefficient" of heat transfer. Thus, the transfer from the hot to the cold end of the series is expressed as,

$$q = UA \Delta t \quad (14)$$

Here q is B.t.u. per hour, A is the specified area in square feet, and Δt is the over-all temperature difference. U is therefore the quantity of heat transferred per hour through 1 sq. ft. of the surface when an over-all temperature difference of 1°F. exists between the outer boundaries of the series of resistances. To use this method with any degree of precision, the values of the coefficient U must have been determined for strictly comparable conditions. Obviously a large error would be introduced if the coefficient for transfer from condensing steam through a metal pipe into boiling water were used to estimate the flow from condensing benzene through a metal pipe into a viscous oil. Bearing

TABLE XVIII.—OVER-ALL HEAT TRANSFER COEFFICIENTS

From	Through	To	Apparatus	Over-all U	Notes
Hot water.....	Stoneware	Ice water in jacket	Stoneware pot	7.0-5.0	With and without agitation respectively
Hot water.....	Lead pipe	Cold water in pipe	Lead cooling coil in tank	253	Very high speed agitation—propeller at 500 r.p.m.
Hot water.....	Lead pipe	Cold water in pipe	Lead cooling coil in tank	90-360	Blade agitator at 0 and at 40 r.p.m.
Hot rosin.....	Steel pipe	Cool but liquid rosin	Double pipe heat exchanger	25	Countercurrent flow
$60^\circ \text{H}_2\text{SO}_4$ at 100°C.	1-in. lead pipe	Cold water in pipe	Lead cooling coil in tank	100	Slow agitation
Gas oil at 460°F.	Steel pipe	Crude oil at 225°F.	Tubular heat exchanger	30	
Tar residue at 600°F.	Steel pipe	Crude oil at 325°F.	Tubular heat exchanger	8	
Steam in coil.....	Lead pipe	Water, not boiling	Kettle	69	Moderate agitation
Steam around tubes	Steel tubes	Air	Air heater	2.3-8.7	Increased with air velocity
Steam in jacket.....	Enameled cast iron	Boiling water	Enameled kettle	85	
Steam in tubes.....	Steel tubes	Cold water	Condenser	170	
Benzol vapor in tubes.....	Steel tubes	Cold water	Condenser	49	

in mind these limitations, one may use the values of U given in Table XVIII when more specific data for a problem are not available.

Variations in Over-all Coefficients.—The fact that the value of U may vary over a considerable range, even in the same

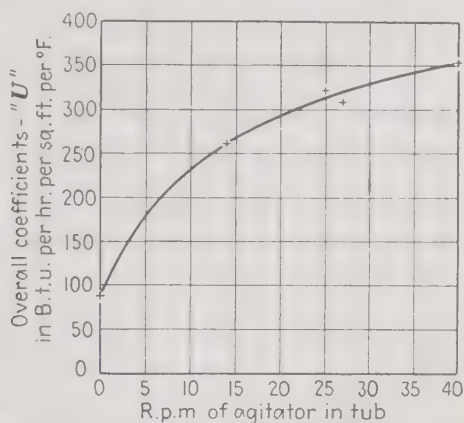


FIG. 6.—Effect of agitation on over-all coefficient of heat transfer.

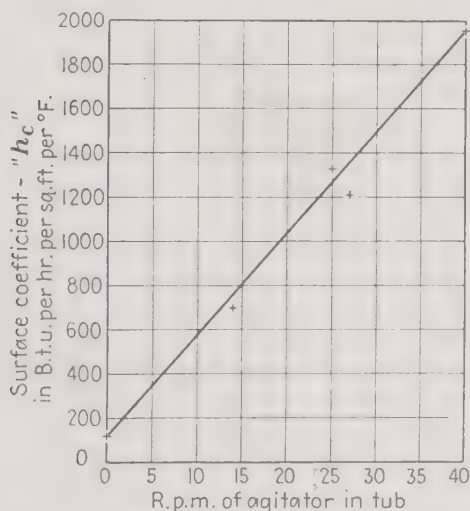


FIG. 7.—Effect of agitation on surface coefficient of heat transfer.

equipment and with the same materials in process, is shown by Fig. 6. The curve is plotted through points representing values of U obtained in a series of tests in an agitated wooden tub, heat being transferred from hot water in the tub to cooling water passing at a substantially constant rate through a lead coil. As the r.p.m. of the blade agitator was increased, the over-all

coefficient increased from less than 100 at 0 r.p.m. to slightly over 350 at 40 r.p.m. By calculating the individual resistances through the inner water film, the metal pipe, and the outer water film, values of the convection coefficient h_c to the metal pipe from the agitated water were derived. These are plotted in Fig. 7.

The relative magnitude of the three individual resistances and of the total resistance ($R = R_1 + R_2 + R_3$) at the various rates of agitation may be seen in Fig. 8. At low agitator speeds, the resistance of the water film on the outside of the pipe was of controlling importance; as the speed was increased, this resistance became small in comparison with that of the pipe itself and of the inner water film. Evidently, further increase in agitation would be of little benefit in decreasing the overall resistance to heat transfer.

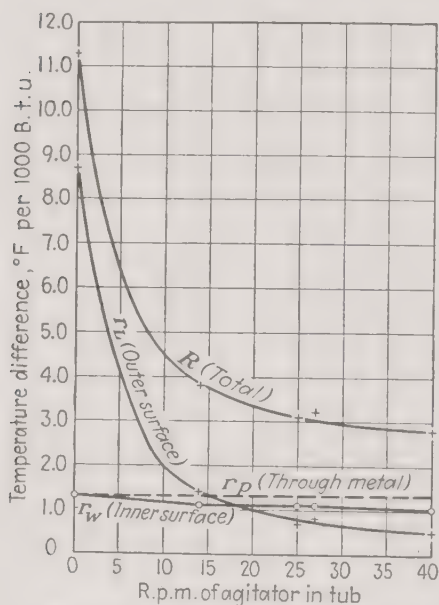


FIG. 8.—Comparison of individual resistances to heat transfer at various rates of agitation.

Average Temperature Difference.—The value of Δt is sometimes, but not always, constant. For problems involving heat loss to the atmosphere from steam at a given pressure in a pipe, it is reasonable to assume that the temperature difference between the pipe surface and atmosphere is constant at all points along

the length under consideration and at all times during the period involved. Likewise, Δt is constant in the transfer from condensing vapor to a liquid boiling at constant pressure and maintained at constant composition throughout the time in question.

It will be evident, however, that in the case where steam in a jacket or pipe coil is heating the contents of a kettle from an initial to a final temperature, the value of Δt must be smaller at the end of the hour than at the beginning. Again, if oil is flowing through a jacketed pipe with condensing steam in the jacket, the value of Δt at the end where the cold oil is entering must be greater than at the end where the heated oil is discharged.

At any point along the pipe, assuming continuous flow of oil, Δt is constant throughout the hour but is different from Δt any other point.

In order to use the heat-transfer formula, therefore, it is necessary to calculate an average temperature difference ($\Delta t_{\text{ave.}}$) whenever the actual Δt varies *regularly during a period of time* or *regularly from point to point* along a heat-transfer surface. Under these conditions, the same type of calculations is made as in the

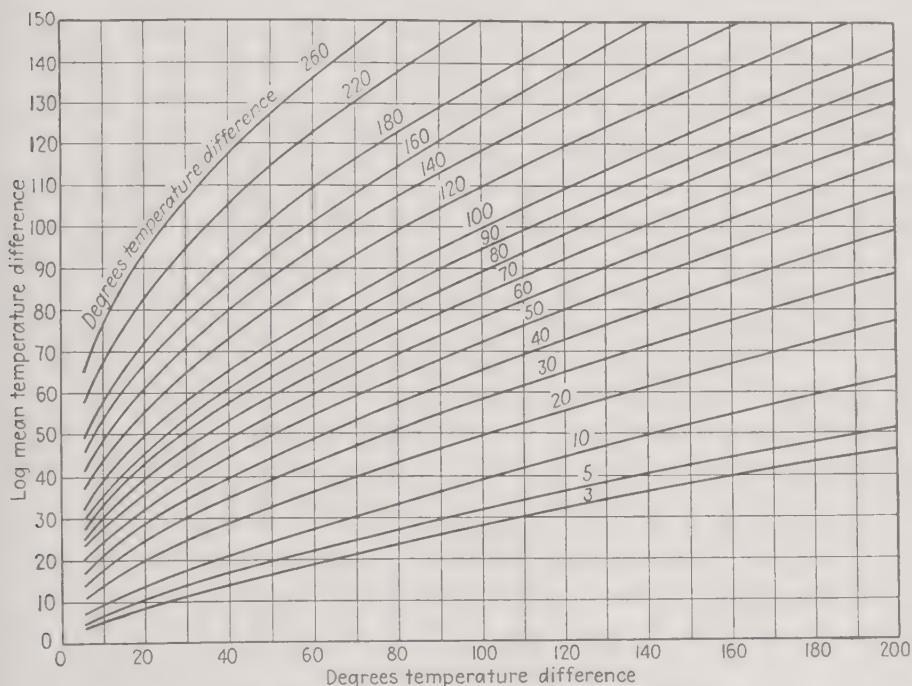


FIG. 9.—Log mean temperature differences.

determination of average areas. That is, calling the larger temperature difference Δt_1 and the smaller Δt_2 , we may use the *arithmetic mean* if Δt_1 is not more than twice as great as Δt_2 , but we must use the *logarithmic mean* when the ratio $\Delta t_1/\Delta t_2$ is greater than 2.0. The formulas are

$$\Delta t_{\text{ave.}} = \frac{\Delta t_1 + \Delta t_2}{2} \quad (\text{arithmetic mean}) \quad (15)$$

$$\Delta t_{\text{ave.}} = \frac{\Delta t_1 - \Delta t_2}{2.3 \log_{10} \frac{\Delta t_1}{\Delta t_2}} \quad (\text{logarithmic mean}) \quad (16)$$

For convenience, logarithmic mean values can be determined from the curves of Fig. 9. Taking one value of Δt along the bottom of the chart (the abscissa), go vertically to the curve marked with the other Δt . The *log mean* Δt is then found at the ordinate of that point of intersection by proceeding horizontally to the scale at the left.

ILLUSTRATIVE PROBLEMS

Illustration 5.—Water is being evaporated in a jacketed enameled kettle from a dilute solution whose boiling point is substantially 212°F. throughout the process. The steam is at a pressure of 10 lb. per square inch gage. The over-all coefficient U has been previously determined to be 85 B.t.u./hr./sq. ft./°F. temperature difference. If the kettle has an effective heating area of 17.0 sq. ft., how many pounds of steam will be condensed in the jacket per hour, assuming radiation loss as 10 per cent of the total?

The temperature of steam at 10 lb. gage pressure (24.7 lb. absolute) is taken from the Steam Tables as 240°F., using the value for 25 lb. absolute as being close enough. Since the boiling water is at 212°F.,

$$\Delta t = 240^{\circ} - 212^{\circ} = 28^{\circ}\text{F.}$$

Using Equation (12),

$$\begin{aligned} q &= UA \Delta t \\ &= 85 \times 17 \times 28 = 40,500 \text{ B.t.u. per hr.} \end{aligned}$$

The heat given up by each pound of steam condensing at 240°F. is found in the Steam Tables to be 952 B.t.u. per pound.

$$\therefore \frac{40,500}{952} = 42.5 \text{ lb. of steam per hr.}$$

to supply heat to boiling solution

The problem states that 10 per cent of the total steam is used to provide for radiation (and convection) losses. That is, 42.5 lb. is 90 per cent of the entire condensate.

$$\therefore \frac{42.5}{0.90} = 47.2 \text{ lb. steam condensed per hr.}$$

Illustration 6.—The over-all coefficient for a certain tubular evaporator, using steam at 20 lb. per square inch absolute and concentrating a solution boiling at 200°F. under a 10-in. vacuum, has been found to be 250 B.t.u./hr./sq. ft./°F. How many pounds of water can be evaporated per hour, the heating surface being 1,000 sq. ft.?

From the Steam Tables, it is found that steam at 20 lb. absolute has a temperature of condensation of 228°F. Then,

$$\begin{aligned}\Delta t &= 228^{\circ} - 200^{\circ} = 28^{\circ}\text{F.} \\ q &= UA \Delta t \\ &= 250 \times 1000 \times 28 \\ &= 7,000,000 \text{ B.t.u. per hr.}\end{aligned}$$

According to the Steam Tables the latent heat of vaporization of water at 200°F. (assuming that the latent heat depends upon the temperature rather than upon the pressure over a solution) is 978 B.t.u. per pound. Therefore,

$$\frac{7,000,000}{978} = 7,160 \text{ lb. of water evaporated per hr.}$$

Illustration 7.—The heat loss from a bare steam pipe, 8.63 in. O.D., 500 ft. long, is found to be 3.14 B.t.u./hr./sq. ft./°F., the pipe being at 360°F. and the air at 60°F. How much steam can be saved per hour by lagging the pipe with 2-in. magnesia covering, assuming that the coefficient from the surface of the pipe after insulating it will be 2.0 B.t.u./hr./sq. ft./°F.? Calculate the temperature of the lagged surface and check the value of $(h_c + h_r)$ from Fig. 5 with the assumed value of 2.0.

The area of the bare pipe is

$$\begin{aligned}A &= \frac{\pi \times 8.63}{12} \times 500 = 1,130 \text{ sq. ft.} \\ \therefore q &= (h_c + h_r)A \Delta t \\ &= 3.14 \times 1,130 \times (360 - 60) \\ &= 1,060,000 \text{ B.t.u. per hr. from bare pipe}\end{aligned}$$

The diameter of the lagged pipe will be $8.63 + 2 \times 2 = 12.63$ in. The outside area (surface of lagging) will be

$$A = \frac{12.63}{8.63} \times 1,130 = 1,650 \text{ sq. ft.}$$

The average area for the heat flow through the magnesia is

$$A_{\text{ave.}} = \frac{1,130 + 1,650}{2} = 1,390 \text{ sq. ft.}$$

Since the heat lost from the pipe flows through two resistances, R_1 being that of the insulation and R_2 that from the surface to the air, the total resistance will be the sum of these. Note that $L_1 = 2 \text{ in.} = 0.167 \text{ ft.}$ Using equation (5),

$$R_1 = \frac{L_1}{k_1 A_{\text{ave.}}} = \frac{0.167}{0.04 \times 1,390} = 0.00300 \text{ thermal ohm}$$

To calculate R_2 , note that $q = (h_c + h_r)A \Delta t = \Delta t/R_2$.

$$\therefore R_2 = \frac{1}{(h_c + h_r)A} = \frac{1}{2.0 \times 1,650} = 0.00033 \text{ thermal ohm}$$

The over-all Δt from pipe to air is still $360^\circ - 60^\circ = 300^\circ\text{F.}$

$$\begin{aligned} \therefore q &= \frac{\Delta t}{R_1 + R_2} = \frac{300}{0.00300 + 0.00033} \\ &= \frac{300}{0.00333} = 90,100 \text{ B.t.u. per hr. loss from pipe when} \\ &\hspace{25em} \text{insulated} \end{aligned}$$

The saving is $1,060,000 - 90,100 = 969,900 \text{ B.t.u. (970,000) per hour.}$ The steam temperature may be taken as substantially the same as the pipe itself. The latent heat of steam at 360°F. is $863 \text{ B.t.u. per pound.}$

$$\therefore \frac{970,000}{863} = 1,120 \text{ lb. steam saved per hr.}$$

To check the temperature of the lagging, let Δt_1 be the difference between the pipe and the outside surface of the lagging. The heat transferred through the lagging is obviously the same as that calculated above as the loss from pipe through lagging and into the air

$$\begin{aligned} q &= \frac{\Delta t_1}{R_1} = \frac{\Delta t_2}{R_2} = \frac{\Delta t}{R_1 + R_2} \\ \therefore \Delta t_1 &= qR_1 \\ &= 90,100 \times 0.003 \end{aligned}$$

$$= 270^{\circ}\text{F.}$$

$360^{\circ} - 270^{\circ} = 90^{\circ}\text{F.}$, calculated temperature on lagged surface

$$\therefore \Delta t_2 = 90^{\circ} - 60^{\circ} = 30^{\circ}\text{F.}$$

From Fig. 5, it is evident that this 30° temperature difference would indicate a value of $(h_c + h_r)$ of about 1.7 instead of 2.0. For greater accuracy, this new value could be substituted to find R_2 and the heat loss recalculated.

Problems

151. If one end of a 3-in. aluminum shaft, 8 ft. long, is at a temperature of 300°C. and the other end is at 150°F. , how much heat is transmitted per hour, neglecting losses from the surface of the shaft?

152. A furnace wall is made up of $4\frac{1}{2}$ in. of carborundum brick, 9 in. of fire brick, and $4\frac{1}{2}$ in. of Sil-O-Cel brick. If the inside of the wall is at 2000°F. and the outside is at 100°F. , what is the heat loss per square foot of wall area per hour?

153. A pipe covering of good magnesia on a 6-in. steam pipe (O.D. = 6.63 in.) is tested by a thermocouple touching the pipe itself and another one 3 in. out from the first. If the first couple registers 350°F. and the second 150°F. , what is the heat loss per foot length of pipe per hour?

154. In Prob. 152, what is the temperature at the joint of carborundum and firebrick and at the joint of fire brick and Sil-O-Cel brick? What percentage of the total resistance is due to each of the three materials in the wall?

155. If the furnace wall in Prob. 152 were circular (I.D. = 3 ft.), what would be the heat loss per square foot of outside wall surface per hour?

156. Calculate the heat loss per 24 hr. from 100 linear ft. of 1-in. standard steel pipe (O.D. = 1.315 in.) carrying steam at 150 lb. per square inch gage pressure if the pipe is lagged with 2-in. magnesia and the outside of the covering is at 90°F. Assume the pipe surface is 1°F. cooler than the steam.

157. A muffle furnace in a room at 70°F. is 5 ft. long, 3 ft. wide, and 2 ft. high, supported on legs 3 ft. from the floor. If the outside of the furnace has an average temperature of 190°F. , what is the heat loss per hour?

158. A steel tank 4 ft. in diameter by 6 ft. high contains a batch of material at 250°C. Assume the outside of the tank to have an average temperature of 150°C. The tank rests on an insulating base but the sides and top are not insulated. If the bottom loses only 10 per cent as much per square foot as the top of the vessel, calculate the heat loss per hour.

159. If the surface temperature of the vertical pipes in a cast-iron steam radiator is 210°F. , how many pounds of steam will be condensed in the radiator per hour if it keeps the room at 70°F. ? The area of the coils is 30 sq. ft. and the steam is at 5 lb. per square inch gage pressure. What per cent of the heat is transferred by radiation? Take $e = 95$ per cent.

160. In a cast-iron kettle, 361 lb. of water was evaporated at atmospheric pressure in 79 min., using 374 lb. of steam at 60 lb. per square inch gage

pressure. The heating surface was 44.5 sq. ft. What was the over-all coefficient U ?

161. In a tubular heater, steam at 165 lb. per square inch gage pressure is around the tubes, and air flows through the tubes. The cross section of the tubes is 0.0789 sq. ft. and the internal heating area is 27 sq. ft. for the thirty-seven $\frac{3}{4}$ -in. tubes, 4 ft. 6 in. long. When the air flows at the rate of 52 lb. of air per square foot of cross section per minute, the over-all coefficient is 4 B.t.u./hr./sq. ft./°F. If the air enters at 70°F., at what temperature does it leave?

162. In Prob. 161, how many pounds of steam were condensed per hour?

163. In a small graining kettle having 8.5 sq. ft. of heating surface, the steam in the jacket was at a temperature of 266°F. Evaporation was 86 lb. of water per hour at atmospheric pressure. What was the coefficient U ?

164. A cast-iron graining kettle has an effective heating area of 36 sq. ft. With steam at 25 lb. per square inch gage pressure in the jacket, and a vacuum of 20 in. of mercury in the kettle, how many pounds of water could be evaporated per hour?

165. In a steam-jacketed enameled kettle holding 60 gal., the heat transfer was measured by boiling water at 212° with steam at 38.7 lb. per square inch absolute pressure in the jacket and measuring the heat absorbed by cooling water in the condenser. The cooling water (6,590 lb. per hour) rose from 73.4 to 85.0°F. Assuming that this heat was due to condensing the steam without further cooling, calculate U , if the heating surface was 13.0 sq. ft.

166. In the kettle of Prob. 165, toluol was evaporated, using steam at 61.5 lb. per square inch absolute pressure. The condenser water (4,570 lb. per hour) entered at 77°F. and left at 84.6°F. What was the value of U for the kettle in this case? How many pounds of toluol were evaporated in 1 hr.? Take the boiling point as 110°C. and the latent heat of vaporization as 156 B.t.u. per pound.

167. Two thousand pounds of rosin per hour at 105°C. are to be heated to 200°C. in a continuous countercurrent heat exchanger by means of hot resin entering at 250°C. and leaving at 155°C. How many feet of $1\frac{1}{2}$ in. O.D. aluminum tubing are needed for the inner pipe of the exchanger? Take the specific heat of the hot resin to be the same as for rosin.

168. If the specific gravity of the materials in Prob. 167 is 1.0, and the outer pipe of the exchanger is 2 in. in inside diameter, calculate the velocities in feet per second of rosin and of resin. The resin is pumped through the inner pipe.

169. A certain still having an effective heating area of 30 sq. ft. is heated by hot oil entering at 290°C. and leaving at 280°C. The organic liquid, whose latent heat of vaporization is 100 B.t.u. per pound, distills at 215°C. at the rate of 400 lb. per hour. What is the value of U ?

170. If the still in Prob. 169 were heated by Dowtherm vapor with an over-all U of 125, what would be the pressure in the heating jackets to distill the same amount of product per hour?

CHAPTER IV

EVAPORATION

The conversion of a liquid into a vapor, leaving behind a solution or a higher boiling liquid, is called *distillation* or *evaporation*. If a solid is left behind, the process is called *drying*. Although these terms are sometimes used interchangeably for the same operation, the term "evaporation" is ordinarily used where the vapor is of no value. This practically limits its use to the removal of water from solutions. This chapter, therefore, deals with the evaporation of water from solutions in order to increase the concentration of the material dissolved in the water.

Essentials.—Two things are essential for evaporation: heat must be supplied and vapor must be removed. The first of these, heat supply, includes the sensible heat to bring the entire solution to its boiling point plus the latent heat of vaporization for the water evaporated. The necessary values are given in the Steam Tables, certain modifications being involved because we are dealing with solutions rather than with pure water. These modifications will be discussed later. Heat may be supplied in several ways:

(a) *Radiation.*—Energy comes from the sun or from radiant gases or solids that can "see" the solution. Primitive salt manufacture involved wetting bundles of sticks with sea water and letting the sun evaporate the water.

(b) *Direct Contact with Hot Gases.*—Hot gases pass over the liquid, which may be dispersed as a spray in the gas or made to flow in thin films over extended surfaces. Much surface and long time of contact are generally needed because of the low rate of heat transfer from gas to liquid.

(c) *Contact with Hot Surfaces.*—The surface may be the walls of the evaporator, as in the case of pans heated by direct fire or electricity or, in the case of jacketed vessels supplied with steam, Dowtherm, or circulating hot oil in the jackets. Frequently, the heating surfaces consist of tubes or coils through the metal of which the heat flows from the heating medium. An attempt

is always made to arrange the heating surface to give the best value of h_c from surface to liquid, various means being employed to increase the velocity of liquid over the surface as much as possible.

The second essential, vapor removal, involves means of causing the vapor to flow away from the evaporating solution so that the vaporization can continue. Unless this is done, the pressure above the solution soon equals the vapor pressure of the water in the solution and boiling stops. Vapor may be removed by diffusion into an inert gas or directly in its pure state. An example of the first of these methods is found in spray chambers, where the liquid gives off vapor without boiling until the inert gas is "saturated," *i.e.*, until the partial pressure of water vapor in the gas corresponds to the vapor pressure of water in the solution at the temperature of the solution. Evaporation stops unless the gas is removed as fast as it becomes saturated.

Evaporation by removal of vapor in the pure state is carried out by boiling, *i.e.*, with the formation of bubbles of vapor throughout the body of liquid. If there is a free vent from the evaporator, the vapors push the atmosphere away and continue to come off as fast as the heat supply permits. It is often desirable to carry out evaporation at pressures below atmospheric, in which case vapor and noncondensable gas must be removed as fast as formed. To avoid pumping huge quantities of material, the vapor goes through a condenser before going to the vacuum pump, so that only gases that cannot be condensed have to be compressed in the pump and discharged against atmospheric pressure. Provision must then be made for removal of the condensate. The condenser itself must be adequate in cooling surface and in circulation of the cooling water.

EQUIPMENT TYPES

The types of evaporators most commonly used are direct-fired pans, spray towers and spray ponds, jacketed vessels, and "tubular" evaporators. Either batch or continuous operation may be employed.

Direct-fired Pans.—These are generally open cast-iron pots, supported on brick settings and fired by gas or oil. They are used where the boiling point of the desired product is too high for other means of heating, *e.g.*, in the manufacture of fused

caustic soda. Thermal efficiency is low, because the short path of travel of combustion gases does not permit effective utilization of these gases, which are discharged at relatively high temperatures. Since the evaporating pans are easily cracked by uneven heating or by sudden chilling, maintenance is high. Removal of product is inconvenient and difficult, whether special discharge nozzles are cast integrally with the pot or the product is dipped or siphoned out.

Spray-type Evaporators.—The most common are those used for cooling hot water by causing part of it to evaporate into the air, thus taking heat away from the remainder, which is then pumped away for cooling purposes. In some cases, a solution is sprayed into hot gas, all of the water being removed and a dry solid produced. This type will be considered later under Drying.

Jacketed Vessels.—This is a common type, especially where some other batch operation is carried out in the same vessel. Thus, a jacketed kettle may be used for a chemical reaction which is then followed by the concentration of the solution. With an anchor-type agitator, coils cannot be used, so that the heating must be done by the jacketed surfaces. The amount of this surface is relatively small and becomes less per unit of volume as the diameter of the kettle becomes greater.

The heating surface available in jacketed horizontal tanks and in vertical kettles, per unit of charge, is shown by Table XIX, together with data on the disengaging surface (free area) of the liquid, etc. It has been found in practice that about 10 lb. of water can be evaporated per square foot of disengaging surface (*i.e.*, free area of liquid) per hour without excessive entrainment, except for very foamy liquids. This assumes a reasonable amount of free space above the liquid (18 to 24 in.) for separation of spray from vapor. It is common practice to fill a kettle only 50 to 75 per cent full, leaving the extra volume for spray separation. Since it is frequently undesirable to subject thin films of the liquid to excessive concentration on hot surfaces, where drying and baking may occur, horizontal vessels are often jacketed only on the lower third of the circumference and vertical kettles may have divided jackets so that the upper portion may be cut out of service when the liquid level falls below the top of that heated section.

TABLE XIX.—COMPARISON OF KETTLES AND TANKS

Kettles having the following characteristics are vertical cylinders with standard dished bottoms, vertical sides being twice the diameter of the kettle in each case. Allowance has been made for discharge nipple on the bottom of each kettle in calculating heating areas. Kettles are jacketed on the bottoms and either half-way (A) or two-thirds of the way (B) up the sides.)

Diameter, ft.	Volume		Jacket area, sq. ft.		Effective jacket area, sq. ft. per cu. ft. of contents						Disengaging area, sq. ft.					
	Cu. ft.	Gal.	A		B		75 % full		50 % full		25 % full		Total	Per cu. ft. of contents		
							A	B	A	B	A	B		75 % full	50 % full	25 % full
2	13.0	97.3	15.9	20.1	1.58	2.07	2.38	2.38	2.88	2.88	3.14	0.323	0.484	0.967		
3	43.8	328.	35.8	45.2	1.09	1.37	1.58	1.58	1.84	1.84	7.08	0.215	0.323	0.646		
4	104.	778.	63.5	80.3	0.813	1.03	1.19	1.19	1.38	1.38	12.6	0.162	0.243	0.486		
5	204.	1,530.	99.3	125.0	0.648	0.817	0.952	0.952	1.10	1.10	19.6	0.128	0.192	0.384		
6	351.	2,630.	143.0	181.0	0.543	0.687	0.792	0.792	0.92	0.92	28.3	0.108	0.161	0.323		

(Tanks having the following characteristics are horizontal cylinders with standard dished ends, horizontal sides being twice the diameter of the tank in each case. Ends are not jacketed. Jackets (*A*) extend around the lower third of the tank, jackets (*B*) extend around the lower half.)

Diameter, ft.	Volume		Jacket area, sq. ft.		Effective jacket area, sq. ft., per cu. ft. of contents						Disengaging area, sq. ft.					
	Cu. ft.	Gal.	A	B	75 % full		50 % full		25 % full		Total			Per cu. ft. of contents		
					A	B	A	B	A	B	75 % full	50 % full	75 % full	50 % full	25 % full	
2	13.5	101	8.37	12.6	0.827	1.24	1.24	1.86	2.48	2.77	7.83	8.72	0.775	1.30	2.32	
3	45.3	349	18.9	28.3	0.555	0.831	0.834	1.25	1.67	1.86	17.6	19.6	0.517	0.866	1.55	
4	107.	800	33.5	50.2	0.418	0.628	0.627	0.941	1.25	1.40	31.3	34.9	0.391	0.650	1.17	
5	210.	1,570	52.3	78.5	0.332	0.498	0.498	0.748	0.997	1.11	48.9	54.5	0.311	0.517	0.932	
6	362.	2,710	75.4	113.	0.277	0.417	0.416	0.625	0.832	0.930	70.4	78.5	0.260	0.432	0.778	

Because of the relatively long unsupported sections of metal in jacketed vessels, it is customary to keep jacket pressures relatively low (*e.g.*, 50 to 75 lb. per square inch). This avoids stay bolts, excessive thickness of metal, etc. Where higher pressures are needed, cast-iron kettles may be used with coils cast into the walls of the vessel, or fabricated sheet-metal kettles may have coils welded to the surface of the body. In such cases, the coils can carry steam at high pressure without danger of rupturing the kettle. Where steam at an elevated

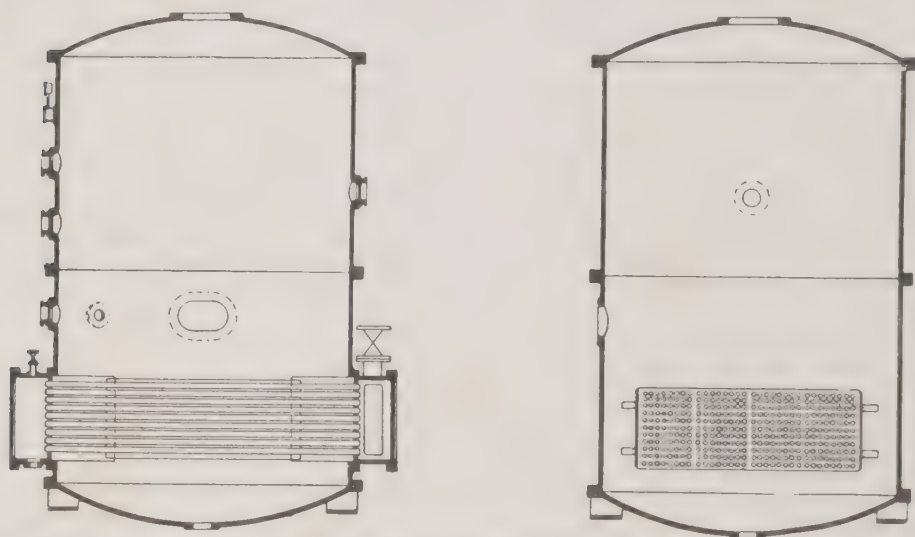


FIG. 10.—Horizontal-tube evaporator. Steam inside of tubes. (*Courtesy of Zaremba Company.*)

pressure is supplied through a reducing valve to a jacket designed for a pressure lower than that of the steam main, a safety valve must be provided to protect the jacket in case of trouble with the reducing valve.

Tubular Evaporators.—Units of this kind are the most common type where considerable quantities of water must be evaporated. Much more surface can be provided, per unit volume of liquid, than is possible with jacketed vessels. Various arrangements of tubes are used in commercial evaporators, steam being either inside or outside of the tubes. In modern practice the first of these two arrangements is generally used only with horizontal tubes. These can be replaced easily and are especially useful where corrosion is severe and cast iron, cast lead, or cast bronze must be used. Because of the relatively short length of

the tubes, both heat transfer and positive removal of noncondensable gases and of condensate are facilitated. This type of evaporator is used for nonviscous solutions that do not form scale or crystals on the tubes. It is generally less expensive than other types in first cost (see Fig. 10).

Instead of steam being inside the tubes, it may be *outside*. Most evaporators now in use involve this arrangement because it permits a rapid movement of solution through the tubes, with better over-all heat transfer and better control of precipitated solids. Several variations of this arrangement include:

The "standard" type, with a "calandria," consists of a section of the body with two tube sheets carrying vertical tubes, a large central tube being provided as a downtake. Steam around the tubes causes liquid to boil up through the main body of tubes; vapor flashes off, and the liquid thus cooled flows through the central downtake and maintains circulation. Tubes are difficult to replace, and the heat transfer is not so good as in other types of more recent design. Solutions carrying suspended solids can be handled with this evaporator but it is not recommended for foamy liquids (see Fig. 11).

The "basket" type has a removable tube section to which a steam pipe leads from the outside of the body. Liquid boils up through the tubes, which are surrounded by steam, and recirculates downward through the annular space between the basket and the wall of the evaporator shell. This type can be used where corrosion necessitates frequent replacement of tubes, but where salt deposition prevents the use of the horizontal tube type.

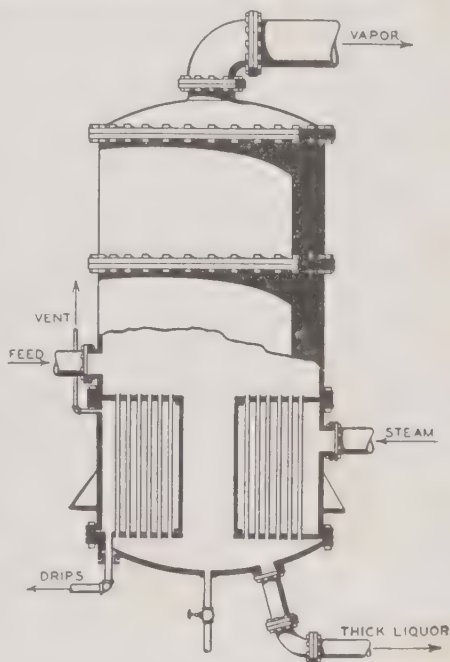


FIG. 11.—Vertical-tube evaporator "standard" type. (Courtesy of Swenson Evaporator Company.)

The "long-tube" or "Kestner" type has a group of vertical tubes, 20 to 23 ft. long, in which the liquor, fed at the bottom, boils and travels upward at an increasingly high velocity as the bubbles formed decrease the density of the mass. The mixture

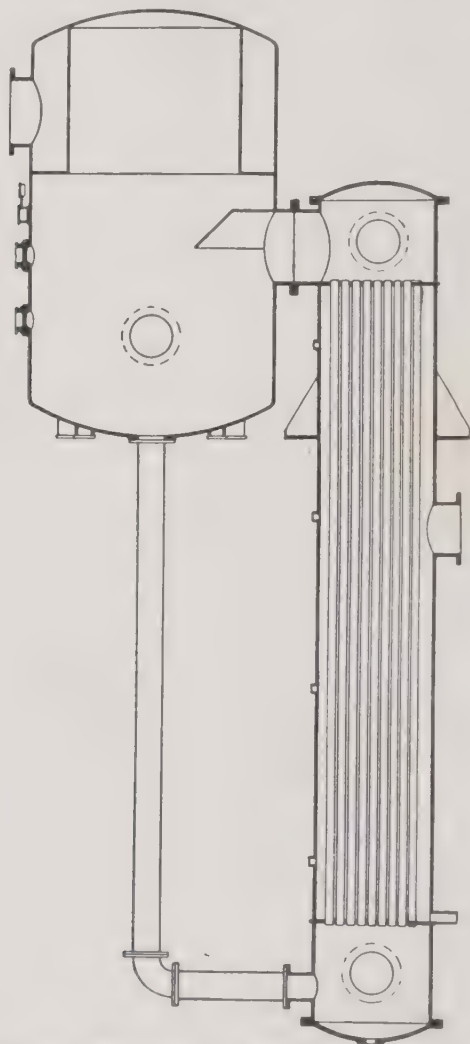


FIG. 12.—Vertical-tube evaporator. Natural circulation through external heater. (Courtesy of Zaremba Company.)

of vapor and spray passes into a chamber where the high velocity permits centrifugal separation of liquid from vapor. The vapor goes to a condenser and the liquid to a receiver or to another similar evaporator for further concentration. Because of the very high velocity of travel, heat transfer rates are high, and any

particle of solution is subjected to heat for only a very short time. In this way, delicate solutions may be evaporated without damage. The need for very accurate control of feed rate and the space requirements limit the application of this type of unit.

Modifications of the Kestner principle employ vertical tubes outside the main body of an evaporator, connected so that liquid boils up through the tubes into the main body, flashes off its vapor, and flows downward to recirculate through the external heater. This type, shown in Fig. 12, carries a low liquid level so that the greater part of each tube contains a rapidly moving mass of bubbles. It is recommended for foamy liquids but not for those that deposit crystals.

The "forced circulation" type (Fig. 13) uses a pump to circulate the liquid at a high rate through the heating tubes. If the velocity is sufficiently great, boiling will not occur until the mass of liquid enters the main body of the evaporator, superheated above its boiling point. Vapors then flash off, crystals may be thrown out of solution, and the liquid flows down to the pump for recirculation. At lower pumping rates, some boiling takes place in the tubes, but the velocity may still be sufficient to prevent adherence of crystals to the tubes. This type is recommended for foamy liquids, viscous liquids, and those that form scale or crystals.

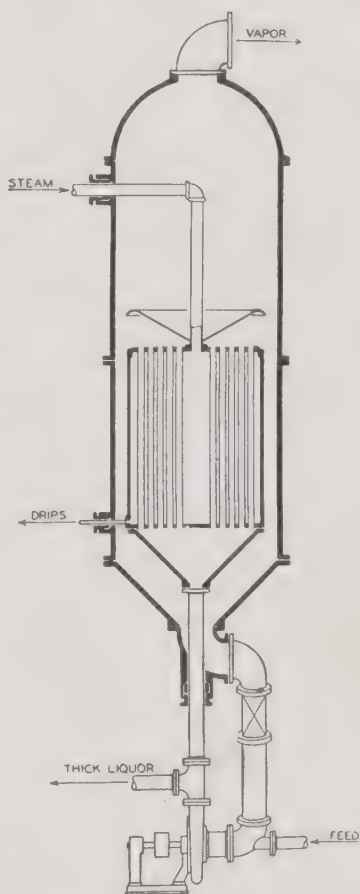


FIG. 13.—Forced-circulation evaporator. (Courtesy of Swenson Evaporator Company.)

OPERATING FACTORS FOR TUBULAR EVAPORATORS

Heat Transfer.—The capacity of an evaporator, *i.e.*, the number of pounds of water that can be evaporated from it per unit of time, may be limited by the rate at which heat can be

transferred into the boiling solution. Since the operating supervisor has no control over the amount of heating surface provided nor its arrangement in the evaporator, his main consideration will be to see that the heating surfaces are kept clean and free from scale, which increases the resistance to heat flow, and that the recommended conditions of steam pressure, liquor level, and vacuum (if any) are maintained. Poor heat transfer may be caused by dirty heating surfaces, by clogged tubes which interfere with liquor circulation, by inadequate discharge of condensed steam because of poorly operating traps, by insufficient venting of noncondensable gases from steam chests, or by maintaining too high or too low a liquor level. All these factors, except the last, have been discussed previously under Heat Transfer. For a given type of evaporator, there is a certain liquor level which gives maximum heat transfer and which is usually covered by the recommendations of the manufacturer.

Crystal Formation.—Some solutions, when concentrated, form crystals. Thus, salt crystals are formed during the evaporation of caustic soda made by the electrolysis of salt brine. In such cases, special "salt catches" or separators are provided so that the crystals may settle in a relatively quiet zone, allowing the clear liquor to return to the evaporating section. The supervisor must see that recommended temperatures and rates of flow are maintained in these separators and that the crystal slurry is removed at proper intervals. The necessity for flushing off heating surfaces to remove adherent crystals during shutdown periods is obvious.

Entrainment and Foaming.—Since the carry-over of solution into the condenser represents a loss of valuable material, special attention must be given to see that this does not occur. Such loss may be in the form of entrained droplets of liquor so small as to travel along in the vapor without settling out, or it may occur when foam builds up and passes out through the vapor line. Enough headroom is ordinarily provided above the boiling liquid in the evaporator body to permit operation at rated capacity without excessive loss. In addition, special separators are usually provided in the path of vapor travel so that the vapors are caused to whirl at such a velocity that centrifugal force throws the liquid particles to the outside of the unit.

There intercepting vanes cause the water to coalesce into drops which are directed back to the evaporator. If losses occur in spite of the separators, the remedy is to reduce the evaporation rate to a point where they stop. In some cases it is possible to introduce an oil or other material into the body of the evaporator, changing the characteristics of the liquid surface and preventing foam or entrainment.

Decomposition of Products.—Some materials are so sensitive to heat that decomposition occurs if temperatures are too high or time of heating is too long. In such cases evaporation is usually carried out under vacuum so that the boiling point of the solution is reduced to a safe temperature. The use of types of evaporators through which the rate of travel is very high is also desirable for such material and is often combined with high vacuum conditions.

Corrosion.—Where the solutions handled are corrosive, it is often necessary to use types of equipment which, otherwise, might not be selected for the job. Thus, lead-lined or brick-lined tanks may be provided, heating being done by coils of lead, Duriron, or Hastelloy, or by "bayonet heaters" of Duriron or tantalum.

AUXILIARY EQUIPMENT

Entrainment Separators.—These have been mentioned in the discussion of Operating Factors. An example of one type is shown in Fig. 14.

Condensers.—These fall into two general classes: (a) surface condensers, in which the cooling water flows through tubes around which the vapors pass, and (b) jet condensers, in which the vapors are contacted directly by the cooling water.

(a) *Surface Condensers.*—These tubular units are used when the condensate is to be kept separate from the cooling water. As shown in Fig. 15, the tubes are generally arranged for multi-pass operation so that the water flows from the inlet end through a certain number of tubes into a section of the head at the outer end so arranged as to direct the flow back through another group of tubes, etc. By this means the water velocity can be kept at such a rate that proper heat transfer on the water side is obtained. As was pointed out in discussing heat transfer, this water film coefficient is of controlling importance, the resistance to heat flow

on the condensing steam side being usually low. Fouling of the tubes by dirt from the water often reduces the heat transfer to a point where the condenser heads must be removed and the tubes cleaned.

(b) *Jet Condensers*.—This type of unit is much cheaper than the tubular type and is installed unless special considerations

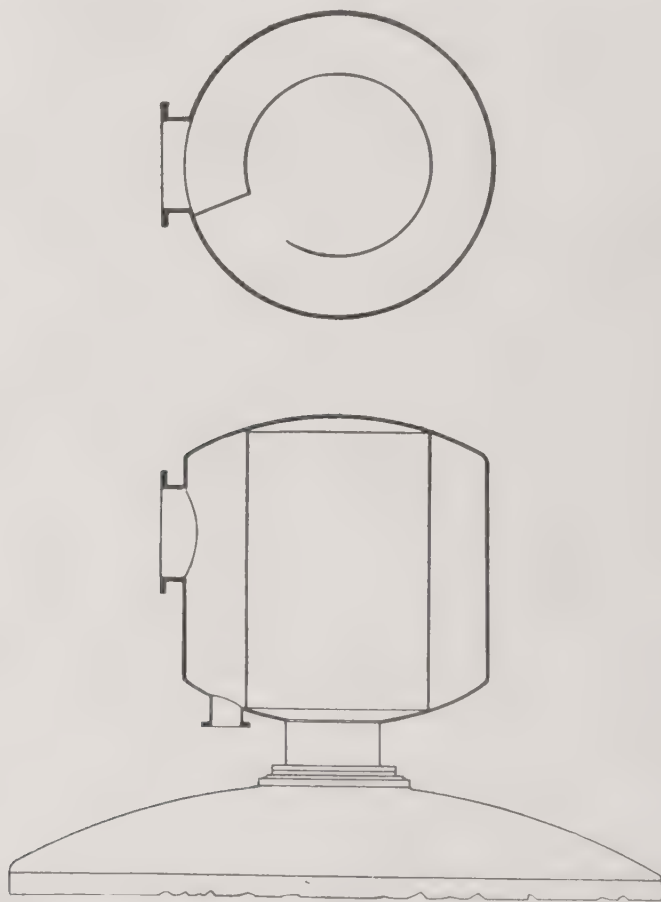


FIG. 14.—Entrainment separator. (Courtesy of Zaremba Company.)

require the tubular unit. It may be arranged, as shown in Fig. 16, so that water and vapors mix at the top and flow down together in "parallel flow," noncondensable gases passing out with the water, or it may be constructed for "countercurrent flow," so that vapors rise against the descending spray of water. In the latter case, noncondensable gases leave at the top, cooled almost to the temperature of the incoming water.

Pumps.—In the case of evaporators operating at atmospheric pressure, the feed liquor is pumped into the evaporator by any suitable pump, and condensate flows from the condenser by gravity. However, when vacuum evaporation is used, the liquor may be drawn into the unit by the vacuum in the evaporator, but the condensate and the noncondensable gases must be pumped out against atmospheric pressure. Also, when the

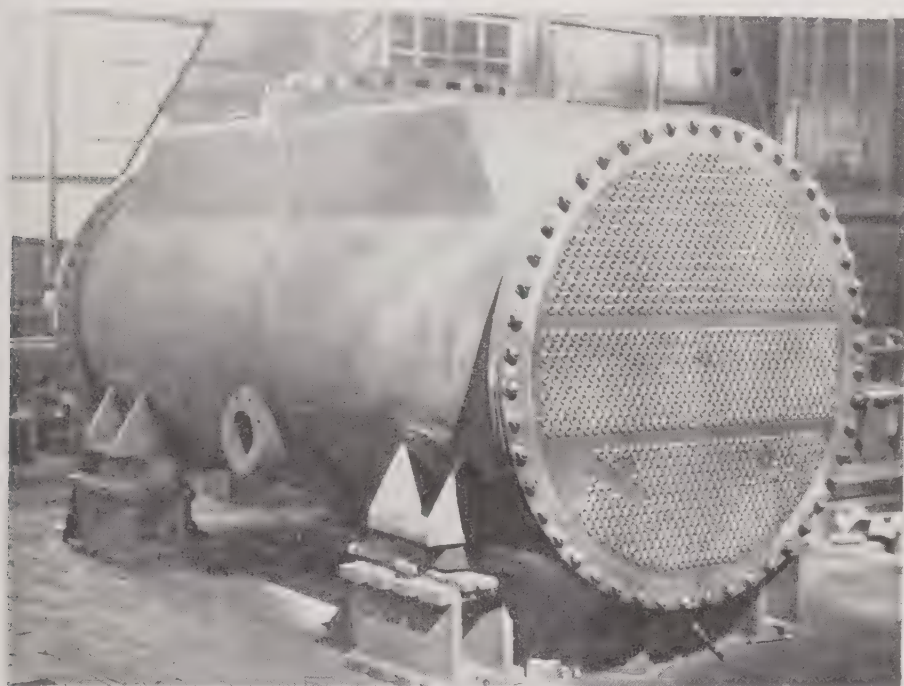


FIG. 15.—Horizontal-surface condenser. Head removed to show tube arrangement. (*Courtesy of Buffalo Foundry & Machine Company.*)

evaporator is operated continuously, the concentrated liquor must be pumped away from the unit.

From a surface condenser, condensate and noncondensable gases may be removed by a “wet vacuum pump,” or a “dry vacuum pump” may be used to remove the gases only. Then a water pump removes the condensate, or it flows out through a “barometric leg,” consisting of a vertical pipe at least 34 ft. long between the condenser and the surface of the water seal into which the pipe dips.

From a jet condenser on a vacuum evaporator, both the cooling water and the condensate with which it mixes must be handled

under vacuum. The same means for gas and water removal are used as noted for the surface condenser.

Instead of dry vacuum pumps for handling noncondensable gases, steam-jet "ejectors" are frequently employed. High

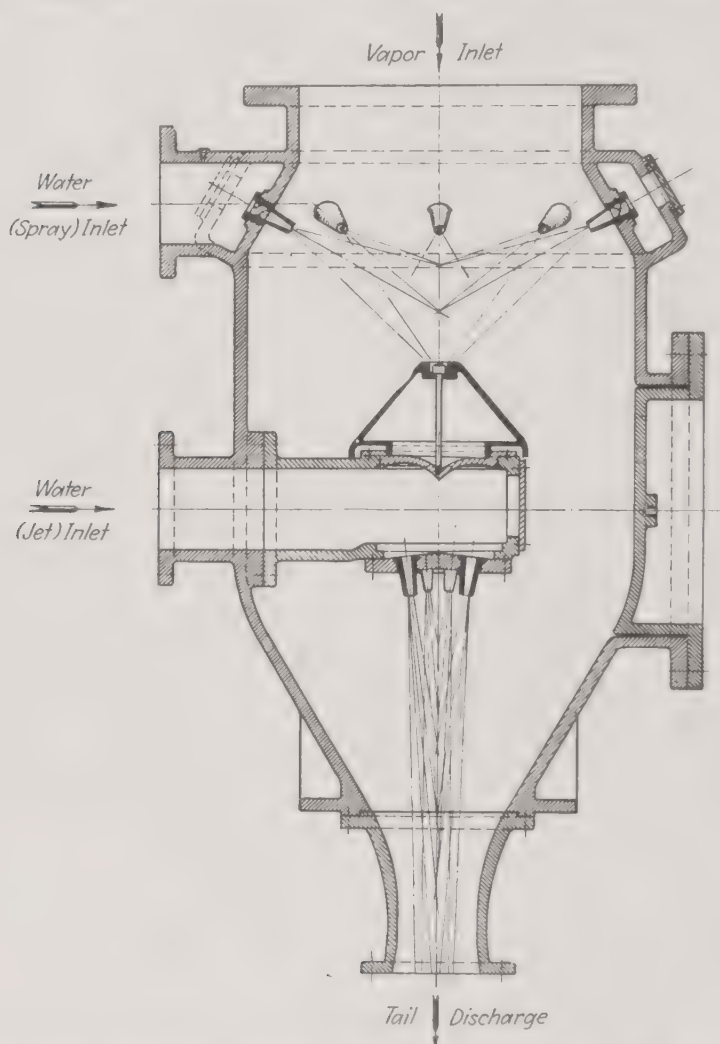


FIG. 16.—Jet condenser. Discharge through barometric leg. (Courtesy of Schutte & Koerting Company.)

velocity jets of steam entrain the gases and discharge them to the atmosphere or to an auxiliary condenser from which another jet compresses them to atmospheric pressure. Such a two-stage unit is shown in Fig. 17.

When vacuum is maintained by means of ejectors, it is important to see that the steam pressure at the inlet to the jets is kept

up to that specified by the manufacturer. Higher pressures do not improve the operation very much on a given jet but pressures lower by only a few pounds per square inch will reduce the vacuum very sharply. Other factors which may cause trouble with these units and which must be watched are corrosion or erosion of the nozzles, which changes the characteristics of the unit, and fouling of the nozzles by solids from the process.

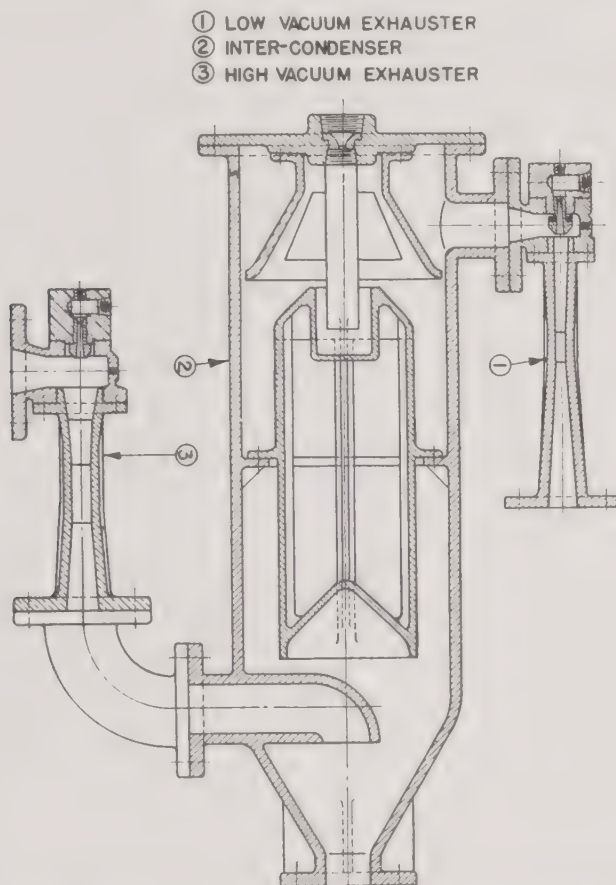


FIG. 17.—Two-stage vacuum ejector. (Courtesy of Schulte & Koerting Company.)

When a barometric leg is used for the discharge of cooling water and condensate, care must be taken to see that no leaks occur in the pipe forming the down leg. Even a pinhole leak in this pipe allows enough air to enter to decrease the density of the water leg. The mixture of water and air is then drawn up into the vacuum jet, thus breaking the vacuum. The water may even suck back into the evaporator itself.

HEAT RECOVERY

Multiple-effect Evaporation.—Since the vapor coming from an evaporator contains all of the latent heat put into it by the steam supplied to that evaporator, this vapor can be used as steam supply to another unit operating under a lower pressure, if the boiling point in the second unit is low enough to permit the vapor to condense in the steam space of the second. The vapor from the second unit can then be used as steam supply to a third evaporator, operating at a still lower pressure and temperature. Each unit in such a series (Fig. 18) is called an

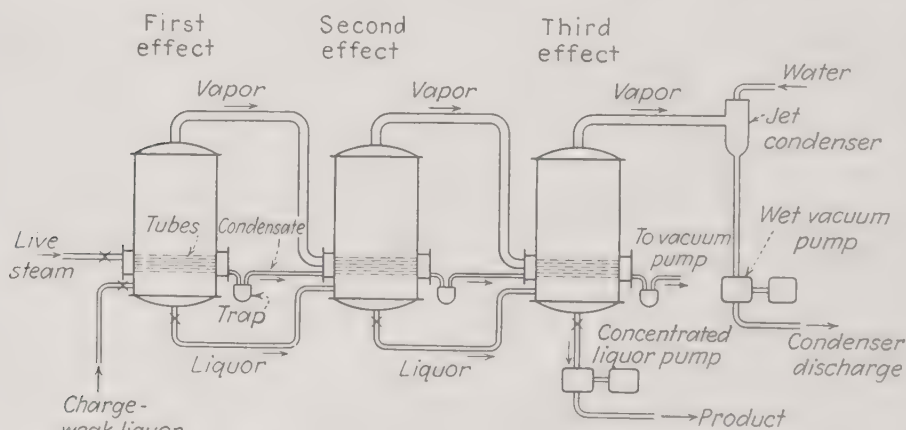


FIG. 18.—Triple-effect evaporator. Parallel flow of liquor and vapor.

“effect,” and the method of re-using the heat is called *multiple-effect evaporation*. Thus, the first effect may be operated at atmospheric pressure, heat being supplied by steam at 15 lb. per square inch; the second effect may be operated at a vacuum of 18 in. of mercury, heat being supplied by the vapor coming from the first effect at atmospheric pressure. The third effect might then operate at a 26-in. vacuum, the steam supply being the vapor at 18 in. of vacuum coming from the second effect. The vapor from the third effect could finally be condensed in a suitable condenser, connected to a vacuum pump. It will be evident that the live steam supplied to the first effect is roughly one-third of that which would have been used to do the entire evaporation in a single effect. Sometimes, where steam is expensive, as many as six effects may be used.

The conditions limiting the first and last effect in a series, and therefore controlling the entire system are called the "terminal conditions." These include

(a) *Maximum Temperature*.—This is the temperature of the steam that can be used in the steam space of the first effect. It is usually limited by the safe working pressure for which the steam space has been designed. The plant boiler pressure is generally much higher than this so that a reducing valve must be provided between the steam main and the evaporator. Another limitation may be the temperature of the tube surfaces with which the solution can be in contact without decomposition.

(b) *Minimum Temperature*.—This is the temperature of the cooling water available for the condenser. Using river water under summer conditions, this may be 85 to 90°F.

(c) *Feed Concentration and Amount*.—Plant conditions establish this factor.

(d) *Product Concentration*.—The solubility and other characteristics of the product and the use for which it is intended determine this.

Limitation of Effects.—The number of effects in a system is limited by several factors. Among these are

(a) *Boiling-point Raising*.—The effect of dissolved material in raising the boiling point of solutions has been discussed previously. In a multiple-effect evaporator this phenomenon becomes a limiting factor in determining the number of effects that can be used. For example, if the solution in a certain effect boils at a temperature 25° higher than corresponds to the pressure in that effect, it leaves the unit with 25° superheat. In the steam space of the next effect, however, it must lose this superheat before condensing and giving up its latent heat. The temperature of the boiling solution in the latter effect must therefore be lower than the preceding unit by this 25° plus the Δt needed for the heat transfer. If we assume that this Δt should be 30°, the drop in temperature between the boiling solutions in the two effects must be 55°. Thus, if the total available temperature difference were 220°, assuming the same drop for each effect, the total number of effects would be limited to four.

(b) *Hydrostatic Head*.—The temperature at which any given solution will boil depends upon the pressure of its surroundings, as

has been pointed out. Thus, at a pressure of 1 lb. per square inch absolute, a 20 per cent solution of caustic soda boils at 113°F. At any point below the surface, however, the pressure is greater than that in the vapor space, owing to the weight of liquid above that point, so that at a depth of 3 ft. the pressure is 1 lb. per square inch plus 1.6 lb. (the weight per square inch of a column of the solution 3 ft. high). That is, $1 + 1.6 = 2.6$ lb. per square inch pressure at a point 3 ft. below the surface. The additional pressure due to liquid is called "hydrostatic head." In this case, the solution at this depth must rise in temperature to 147°F. before boiling. Obviously, the greater the depth of liquid, the higher will be the temperature to which the solution is heated before boiling. The actual boiling point in the evaporator, therefore, will be intermediate between that at the surface and that at the depth where boiling begins.

The vapor formed at points below the top of the liquid in an evaporator expands as it rises to the surface and comes off at equilibrium with that surface solution. Thus, the additional Δt which was used to produce this vapor is not available for the next effect. Like the B.P.R. due to material in solution, the result of hydrostatic head is to limit the possible number of effects in a system.

(c) *Cost of Equipment.*—Since the total available temperature difference, if applied to one unit only, would require much less heating surface than if divided among several units, it is evident that the equipment cost for the evaporators themselves will be proportional to the number of effects. Consequently, the saving in steam must be balanced against the increased overhead charge (interest, depreciation, etc.) to determine the most economical number of effects. At the same time, account must be taken of the decrease in condenser water as additional effects are added. Operation of a multiple-effect system is somewhat more complicated than for a single unit, and maintenance costs are higher. In general, more than four effects are seldom found to be economical.

Recompression.—The latent heat in the vapor from an evaporator may be re-used as noted above by the multiple-effect principle, or it may be made available for re-use at the pressure of the original steam space by compressing it to the pressure of the live steam entering originally. Such compression could be

effected by mechanical pumps but would require large compressors because of the high specific volume of the vapors. It can, however, be accomplished by a steam jet booster using high-pressure steam, as illustrated by Fig. 19. The resultant steam is fed to the steam space of the unit, the excess (equivalent to the high-pressure steam added) being bled off for other uses.

Commercial installations of this sort are now in operation. It is claimed that the steam economy generally corresponds to that of a three-effect system. However, conditions must be maintained very carefully at the point established for the design, and there is not much flexibility. The best application appears to be to a small unit, operating under steady, well-established load conditions.

Self-evaporation.—In a continuous, multiple-effect system the feed may enter into the effects in various ways. That is, in a "counterflow" system the dilute feed may enter the last effect, then be pumped to the next to the last, which is at a higher pressure and temperature, and so on, finally leaving the first effect at the temperature of that unit.

On the other hand, it may enter the first effect and flow on under the constantly decreasing pressure of successive units until it is pumped out of the last one under the highest vacuum. This is called "parallel flow." In the latter method the liquor from the first effect is at a temperature greater than its boiling point in the second unit, so that when it enters the latter, a certain amount of sensible heat is available to "flash off" a portion of the water contained in it, just as condensate from a steam coil flashes part of its weight as

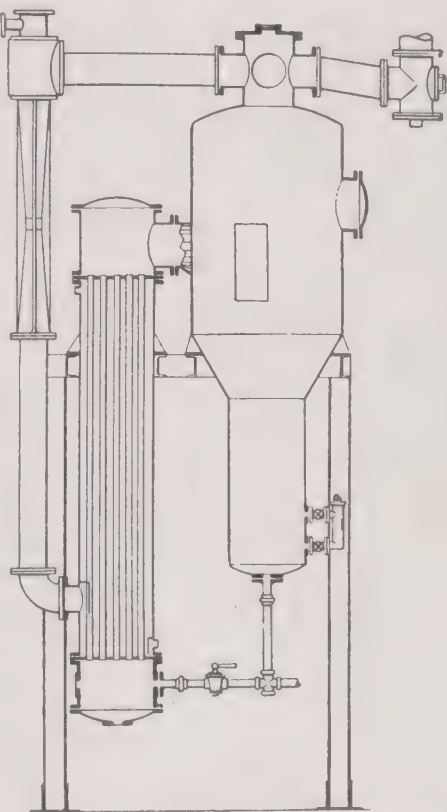


FIG. 19.—Single-effect evaporator, with thermo-compressor. (Courtesy of Buffalo Foundry & Machine Company.)

vapor when it is discharged by a trap into the air. This flashing of vapor by excess sensible heat is called "self-evaporation."

OPERATING DIFFICULTIES IN MULTIPLE-EFFECT SYSTEMS

Air Leaks.—Any system under vacuum is subject to air leaks through valve stems, gaskets on flanges and sight glasses, stuffing boxes of pumps, etc. The effect of such leakage is to cut down heat transfer in the steam space of the unit receiving the vapor and air mixture. The amount of air to be removed from that steam space is also increased. All air, whether entering with the original steam, in the feed liquor, or from leaks, must be removed continually. This may be done by bleeding direct to the condenser or into the steam space of the next effect and thus finally to the condenser. Since the capacity of the vacuum pump, as well as the heat-transfer rate of the condenser, is fixed by the original design, any excess air over the normally anticipated amount will cut down the evaporating capacity of the system.

Steam Leaks.—Since tubes rolled into tube sheets may leak, steam sometimes passes directly into the liquor space of one effect and goes on with the vapor to the next effect. Such steam, therefore, does only a part of the intended work and so decreases the economy of the system. It is therefore advisable to check any apparent rise in the capacity of part of the system at the expense of an earlier part or when accompanied by an increase in total live steam usage, since this indicates a steam leak in the heating section of the effect preceding that in which capacity increases.

CALCULATIONS

The vapor pressure of water below 212°F. (*i.e.*, vacuum conditions) is given in Fig. 20. In solving problems, the following *assumptions* may be made:

1. **Boiling-point raising (B.P.R.)** is the *same number of degrees* at one pressure as at another. That is, the B.P.R. for a solution of 70.1 parts of sodium hydroxide per 100 parts of water is 54°F. at atmospheric pressure, making the boiling point 266°F. Then, at a pressure of 1 lb. per square inch, absolute, where the boiling point of water is 102°F., this solution will be assumed to boil at $102^{\circ} + 54^{\circ} = 156^{\circ}\text{F.}$ This assumption is not exact, more nearly correct values being obtained on the basis that the ratio

of the vapor pressure of a given solution to the vapor pressure of pure water at the same temperature is constant. However, it is convenient and is used in the illustrative problems.

2. **Heat to vaporize** a pound of water from a solution is the latent heat of water corresponding to that temperature at which it is vaporized, not the latent heat of water at the pressure in the effect. Thus, in the case of the caustic solution mentioned in the preceding paragraph, the heat required to vaporize 1 lb.

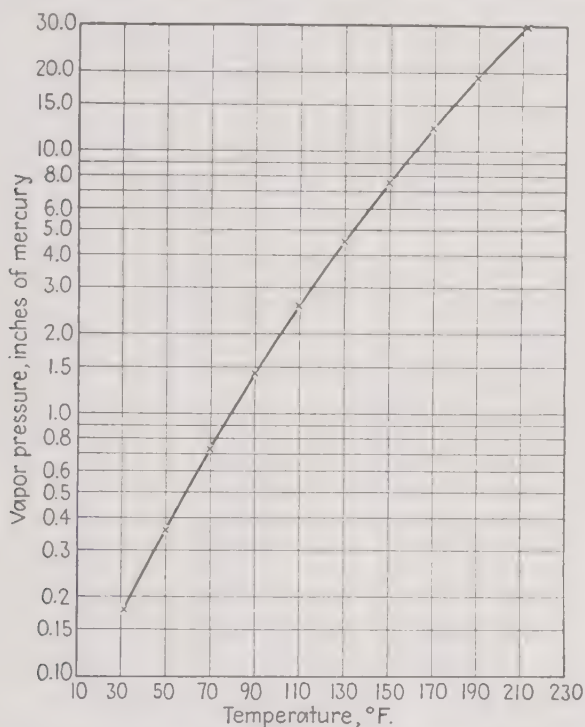


FIG. 20.—Vapor pressure of water below 212°F.

of water from the solution boiling at 156°F. and at a pressure of 1 lb. per square inch, absolute, is taken as 1004 B.t.u. rather than 1036, the latter being the latent heat of pure water at 1 lb. per square inch, the former being that of pure water at 156°F.

3. **Effect of hydrostatic head** is determined by adding *half* the weight of the column of liquid to the pressure in the vapor space and taking this sum as the average pressure at which the solution is boiling.

4. **Specific heat of a solution** is equal to the fraction of pure water present. That is, if a solution contains 90 per cent water

and 10 per cent dissolved solid, the specific heat is taken as 0.90; if it contains 85 per cent water, the specific heat is taken as 0.85. This assumption should not be used, of course, if the actual value of the specific heat of a given solution is available.

ILLUSTRATIVE PROBLEMS

Illustration 1.—In a 2-ft.-diameter Semi-Works experimental kettle, 20 gal. of water is evaporated from a 75-gal. solution in 4 hr., the rate being limited by foaming of the solution. (a) What is the largest size of batch that could be handled in a 6-ft.-diameter plant kettle so that the evaporation from the same initial to the same final concentration would take the same length of time, 4 hr.? (b) How full is each kettle at the start and finish if the specific gravity is 1.15 at the start and 1.20 at the end of evaporation?

(a) From Table XIX, it is noted that the disengaging area, *i.e.*, the surface from which the water evaporates, is 3.14 sq. ft. for a 2-ft.-diameter kettle and 28.3 sq. ft. for a 6-ft.-diameter kettle. The rate of evaporation in the experimental kettle is

$$\frac{20 \times 8.33}{4 \times 3.14} = 13.3 \text{ lb. of water per sq. ft. disengaging surface per hr.}$$

$$4 \times 13.3 \times 28.3 = 1,510 \text{ lb. of water that can be evaporated in 4 hr. from the plant kettle}$$

$$\frac{1,510}{8.33} = 181 \text{ gal. of water from the plant kettle in 4 hr.}$$

Since this corresponds to the Semi-Works evaporation of 20 gal. from a 75-gal. batch,

$$181\frac{1}{2} \times 75 = 679 \text{ gal. in plant batch}$$

(b) According to Table XIX, assuming that the dimensions are "standard," *i.e.*, the vertical side twice the kettle diameter and the bottom having the standard dish, the 2-ft.-diameter kettle has a volume of 97.3 gal. and the 6-ft.-diameter kettle has a volume of 2,630 gal. Since the original solution in the small kettle was 75 gal., the kettle was

$$\frac{75 \times 100}{97.3} = 77.0\% \text{ full at the start}$$

For the plant kettle, the 679-gal. batch shows

$$\frac{679 \times 100}{2,630} = 25.8\% \text{ full at the start}$$

The original solution, having a specific gravity of 1.15, would weigh

$$\begin{aligned} 75 \times 8.33 \times 1.15 &= 718 \text{ lb. in small kettle} \\ 679 \times 8.33 \times 1.15 &= 6,500 \text{ lb. in large kettle} \end{aligned}$$

Subtracting the weight of water removed in each case, the remainder is

$$\begin{aligned} 718 - (20 \times 8.33) &= 718 - 167 = 551 \text{ lb. solution in small kettle} \\ 6,500 - 1,510 &= 4,990 \text{ lb. solution in large kettle} \end{aligned}$$

Dividing by the weight per gallon at a specific gravity of 1.20,

$$\begin{aligned} \frac{551}{8.33 \times 1.20} &= 55.1 \text{ gal. remains in small kettle} \\ \therefore \frac{55.1 \times 100}{97.3} &= 56.6\% \text{ full at end of evaporation in Semi-Works} \\ &\text{kettle} \end{aligned}$$

$$\begin{aligned} \frac{4,990}{8.33 \times 1.20} &= 499 \text{ gal. remains in large kettle} \\ \therefore \frac{499 \times 100}{2,630} &= 19.0\% \text{ full at end of evaporation in plant} \\ &\text{kettle} \end{aligned}$$

Illustration 2.—Five thousand pounds per hour of 10 per cent sodium hydroxide solution is fed at 70°F. to the second effect of a double-effect counterflow evaporator where the boiling point is 158°F. The product leaves the first effect as 50 per cent NaOH, boiling at atmospheric pressure at a temperature which has been increased 5°F. by the hydrostatic head. The temperature difference between the steam in the chest of the first effect and the boiling solution is 30°F. Calculate:

- Pounds of product per hour.
- Pounds of water evaporated per hour by the whole system.
- Sensible heat required by feed liquor entering the system.
- Pressure of steam used.

(a) The solution, charged hourly, contains

$$0.10 \times 5,000 = 500 \text{ lb. } 100\% \text{ NaOH}$$

Since the product is 50 per cent NaOH,

$$\frac{500}{0.50} = 1,000 \text{ lb. of } 50\% \text{ NaOH produced per hr.}$$

(b) The water evaporated must be the difference between the charge and the product.

$$5,000 - 1,000 = 4,000 \text{ lbs. of water evaporated per hr.}$$

(c) Since the specific heat of the weak solution is not given, use assumption 4 from the text, that the specific heat is the same as the fraction of water in the solution. In this solution, the water is 0.9 of the weight.

$$\therefore 5,000 \times 0.9 (158^\circ - 70^\circ) = 396,000 \text{ B.t.u. per hr. sensible heat}$$

(d) According to Table VII, the boiling point of 50 per cent NaOH solution at atmospheric pressure is 289°F . Since the problem states that the average temperature of the solution has been increased 5°F . by the hydrostatic head and since the steam temperature is 30°F . higher than this,

$$30^\circ + (289^\circ + 5^\circ) = 324^\circ\text{F.}, \text{ the steam temperature}$$

From the Steam Tables, this temperature corresponds to a pressure of 94.8 lb. per square inch absolute.

$$94.8 - 14.7 = 80.1 \text{ lb. per sq. in. gage pressure}$$

Illustration 3.—A parallel-flow triple-effect evaporator is concentrating a certain solution, entering at 65°F . and containing 10 per cent solids, to a product containing 60 per cent solids under the following conditions:

Effect	Operating pressure or vacuum	Steam chest pressure	Concentration of boiling solution, %	Depth of boiling solution, ft.
1	Atmospheric	25 lb. per sq. in. gage	20	4.1
2	14 in. of mercury (vacuum)	Atmospheric	40	3.5
3	28 in. of mercury (vacuum)	14 in. of mercury (vacuum)	60	3.0

The condensate from the steam chest of the first effect passes through a trap into the steam chest of the second, and the condensate from the second passes in the same way to the steam chest of the third effect. Part of the vapor from the first and from the second effect is withdrawn for use in another service.

The following data are available for the various solutions:

Solids, %	Specific gravity at boiling point	Boiling point at atmos- pheric pressure, °F.
10	1.05 (at 65°)	213
20	1.10	216
40	1.30	227
60	1.50	250

Calculate, per 1,000 lb. of dilute solution charged:

- Gallons of feed to each effect.
- Pounds of water evaporated in each effect.
- Pounds of 60 per cent solution produced.
- Pounds of water evaporated in second effect by "self-evaporation."
- Pounds of water evaporated in second effect by "flashing" of condensate from first steam chest.

(a) Per 1,000 lb. of entering solution, which is 10 per cent solids, the solids content of the feed is

$$0.10 \times 1,000 = 100 \text{ lb. of solid} \quad \therefore 900 \text{ lb. of water}$$

Since the same amount of solids enters each effect,

$$\frac{100}{0.20} = 500 \text{ lb. of solution from first to second}$$

$$\frac{100}{0.40} = 250 \text{ lb. of solution from second to third}$$

$$\frac{100}{0.60} = 167 \text{ lb. of solution from third, as product}$$

From the specific gravity values given, the volume in gallons (per 1,000 lb. entering solution) is then found to be

$$\frac{1,000}{8.33 \times 1.05} = 114 \text{ gal. feed to first effect}$$

$$\frac{500}{8.33 \times 1.1} = 54.5 \text{ gal. from first effect to second}$$

$$\frac{250}{8.33 \times 1.3} = 23.1 \text{ gal. from second to third}$$

(b) The water evaporated in each effect is found by subtracting the calculated weights of solution leaving each effect from the weight of solution entering each effect.

$$1,000 - 500 = 500 \text{ lb. of water evaporated in first effect}$$

$$500 - 250 = 250 \text{ lb. of water evaporated in second effect}$$

$$250 - 167 = 83 \text{ lb. of water evaporated in third effect}$$

(c) This has already been calculated in (a) as 167 lb. of 60 per cent solution produced per 1,000 lb. of dilute feed.

(d) From the first effect, it has been shown that 500 lb. of 20 per cent solution flows to the second effect. At the average temperature of the first effect, this solution is "superheated" with respect to the pressure of the second effect and can therefore evaporate an amount of water equivalent to the heat given up in cooling to the boiling point of the second effect solution.

The depth of boiling solution in the first effect is 4.1 ft. so that the average hydrostatic head may be taken as 50 per cent of this, or 2.05 ft. of solution, whose specific gravity is 1.10. The increase in pressure equivalent to this is

$$\frac{2.05 \times 1.10 \times 12}{13.6} = 1.99 \text{ in. of mercury}$$

The pressure above the boiling solution is atmospheric, so that the average pressure of the boiling solution, corrected for hydrostatic head is

$$29.9 + 1.99 = 31.89 \text{ in. (31.9 in.) of mercury}$$

Converting this to pressure in pounds per square inch,

$$\frac{31.9}{29.9} \times 14.7 = 15.7 \text{ lb. per sq. in. absolute}$$

It will be seen from the Steam Tables that pure water at this pressure boils at 215°F. Since the boiling point of the 20 per

cent solution at atmospheric pressure is given as 216° in the tabulated data, this indicates a B.P.R. of 4°F . According to assumption 1 in the text, this number of degrees is to be added to the boiling point of pure water at the given pressure.

$$\therefore 215^{\circ} + 4^{\circ} = 219^{\circ}\text{F.}, \text{ B.P. of solution in first effect}$$

In the second effect the pressure above the boiling solution is given as 14 in. of mercury vacuum.

$$\therefore 29.9 - 14 = 15.9 \text{ in. of mercury pressure}$$

The hydrostatic head, calculated as before is

$$\frac{3.5}{2} \times 1.30 \times \frac{12}{13.6} = 2.01 \text{ in. of mercury}$$

Adding this to the pressure above the solution gives

$$15.9 + 2.01 = 17.91 \text{ in. (17.9 in.) of mercury, average pressure}$$

From the Steam Tables, water at this pressure boils at 187°F . For the 40 per cent solution, the B.P.R. at atmospheric pressure is

$$227^{\circ} - 212^{\circ} = 15^{\circ}\text{F}.$$

Adding this amount to the boiling point of water at the average pressure,

$$187^{\circ} + 15^{\circ} = 202^{\circ}\text{F.}, \text{ boiling point of solution in second effect.}$$

The heat given up by the solution passing from the first to the second effect can now be calculated, assuming the specific heat to be the same as the fractional water content (0.80). Then,

$$\begin{aligned} q &= 500 \times 0.80 (219^{\circ} - 202^{\circ}) \\ &= 500 \times 0.80 \times 17 = 6800 \text{ B.t.u. available for "self-evaporation"} \end{aligned}$$

The latent heat in the second effect would actually be utilized *at the surface* of the solution, where the pressure is 15.9 in. of mercury. At this pressure pure water boils at 182°F ., so that, adding the B.P.R. due to concentration, which has been shown to be 15°F ., the temperature at the surface of the boiling solution would be

$$182^{\circ} + 15^{\circ} = 197^{\circ}\text{F}.$$

From the Steam Tables, the latent heat of vaporization at this temperature is 980 B.t.u. per pound of water.

$$\therefore \frac{6,800}{980} = 6.94 \text{ lb. of water vaporized by "self-evaporation" per } 1,000 \text{ lb. of dilute solution entering the system}$$

(e) The steam used in the steam chest of the first effect, neglecting radiation loss, is the amount needed to heat 1,000 lb. of dilute solution from 65°F. to the average boiling temperature of the first effect (219°F.) and to evaporate 500 lb. of water at the temperature of the liquid surface in that effect. The specific heat is assumed to be 0.90. The latent heat of vaporization corresponds to the boiling point of the solution *at the surface*, where atmospheric pressure prevails. This boiling point has been given as 216°F. for the 20 per cent solution, the latent heat of vaporization at this temperature being calculated at 968 B.t.u. per pound by interpolation in the Steam Tables. The total heat transferred from the steam is, therefore

$$\begin{aligned} q &= 1000 \times 0.90(219 - 65) + 500 \times 968 \\ &= 900 \times 154 + 500 \times 968 \\ &= 138,600 + 484,000 = 622,600 \text{ B.t.u. (623,000)} \end{aligned}$$

The steam in the first steam chest is at 25 lb. per square inch gage pressure, or 39.7 lb. per square inch absolute. This corresponds to a temperature of 267°F. and a latent heat of 934 B.t.u. per pound.

$$\therefore \frac{623,000}{934} = 667 \text{ lb. of steam condensed in the first steam chest}$$

The pressure in the second steam chest is atmospheric so that this condensate would give up heat by flash evaporation as it cools to 212°F.

$$667 \times 1.0 \times (267^\circ - 212^\circ) = 667 \times 55 = 36,700 \text{ B.t.u.}$$

This heat is used for evaporating water from the second effect, just as though it had entered the steam chest as fresh vapor. The latent heat in the second effect has been shown to be 980 B.t.u. per pound.

$$\therefore \frac{36,700}{980} = 37.4 \text{ lb. of water evaporated in second effect by}$$

“flashing” of condensate, based on 1,000 lb. of dilute feed to the system

Problems

171. From a jacketed kettle, 5 ft. in diameter and 10 ft. deep, how many pounds of water could be evaporated per hour without excessive priming? From a horizontal tank of the same dimensions, how many pounds could be evaporated? Assume the kettle or tank to be half full of boiling water in each case.

172. A Semi-Works kettle, 24 in. in diameter, has a volume of 97 gal. From an experimental batch of material, 125 lb. of water is evaporated in 3 hr. Estimate the time to evaporate the water from a batch 10 times this size in a 1,530-gal. plant kettle, 5 ft. in diameter, assuming the Semi-Works and the plant batch to have corresponding initial and final concentrations.

173. If the solution boiling in the Semi-Works kettle of Prob. 172 starts boiling at 102°C. and finishes in 3 hr. at 106°C., the over-all heat transfer coefficient from steam to solution being 125 B.t.u./hr./sq. ft./°F., steam being provided at 30 lb. per square inch gage pressure, how many square feet of jacketed surface would be required?

174. Assume that the evaporation from the Semi-Works kettle of Prob. 173 is to be done with hot oil, entering the jacket at 250°C. and leaving at 230°C., and that the over-all coefficient from hot oil to boiling solution is 20 B.t.u./hr./sq. ft./°F. How many square feet of jacketed surface would be required?

175. For the plant kettle of Prob. 172 the total batch is 750 gal. of a 10 per cent solution of a nonvolatile material, the specific gravity being 1.08, entering the kettle at 70°F. Heating and evaporation are to be done by a coil made of 1½-in. O.D. aluminum tubing, using steam at 50 lb. per square inch gage pressure. Assuming that the over-all coefficient is the same as in the Semi-Works kettle and that an individual coil should not exceed 400 diameters in length, design the heating coil or coils for this kettle.

176. In Prob. 175, what is the final concentration of the batch? How many pounds of steam would be required per batch, assuming that the radiation loss is 10 per cent of the total heat usage?

177. The water evaporated from the plant kettle of Prob. 172 is to be condensed by a surface condenser made up of 1-in. aluminum tubes, 5 ft. long. Water enters at 80°F. and leaves at 120°F., flowing around the outside of the tubes. The over-all coefficient for the condensation is 100 B.t.u./hr./sq. ft./°F. How many tubes are needed?

178. A continuous, horizontal-tube evaporator is fed with 2 per cent caustic soda solution at 65°F., and the product, continuously discharged at 110°C., contains 30 lb. of NaOH per 100 lb. of water. The over-all coefficient of heat transfer is found to be 300. Steam is available at 30 lb. per square inch gage pressure. How many square feet of surface are needed per 100 lb. of dilute liquor per hour?

179. In Prob. 178, assume that the evaporator is operated at a vacuum of 26 in. of mercury, that the boiling liquid (sp. gr. 1.3) is 4 ft. deep, and that heating is done by steam at 6 in. of mercury vacuum. Calculate the heating surface needed for a production of 5,000 lb. of the strong caustic liquor per hour.

180. Distilled water is being produced from a very soft but polluted river water. A continuous single vacuum pan is employed with steam at 30 lb. per square inch gage pressure; daily production is 30,000 gal. of distilled water; the system is blown out once daily. The present evaporator, as installed, cost \$4,200; the condenser, pump, and other auxiliary apparatus, \$940. Of the total, 30 per cent must be charged off to cover fixed charges (interest, taxes, etc.), depreciation, and maintenance per year. Steam costs 37 cents per million B.t.u., and the heat consumption is 1040 B.t.u. per pound of water evaporated. Operating expenses, *i.e.*, all other items, including labor, are \$14.20 per 24-hr. day. Would it pay to install additional effects in this system, terminal conditions remaining the same? If so, how many? Assume steam consumption inversely proportional to the number of effects in the series.

181. The condensed steam in the steam chest of the first body of a multiple-effect evaporator is at a temperature corresponding to a vacuum of 0.5 in. of mercury. This water flows to the steam chest of the second body, where the vacuum is 14 in. of mercury. Calculate the increased evaporation in the second body due to the flashing of this condensate, expressed as additional pounds of water evaporated in the second body per 100 lb. of hot water from the first steam chest. The water in the second body is evaporating at 20 in. of mercury vacuum. Neglect any B.P.R.

182. The solution from the first body in Prob. 181 flows into the solution space of the second. Neglecting its B.P.R. and assuming its specific heat to be 0.9, calculate the self-evaporation, expressed as pounds of water evaporated per 100 lb. of solution entering the second effect.

183. A quadruple-effect, horizontal-tube evaporator having 1,470 sq. ft. of heating surface in each effect was tested during the concentration of "black liquor" from the sulphate pulp process. The following data were taken:

	Feed	Effect				Product
		I	II	III	IV	
Solids per hour.....	2830					2830
Weight per cubic foot of liquor..	66.5	67.6	69.9	73.5	85.2	85.2
Pounds of H ₂ O per pound of solid	8.21	6.27	4.29	2.68	0.681	0.681
Specific heat.....	0.946	0.931	0.906	0.864	0.700	0.700
Condensate, pound per hour....		7540			15,650	
Steam pressure, pounds per square inch absolute.....		20.0	14.7	11.5	8.1	
Liquid temperature, °F. (average)	150	215	205	190	142	142

Calculate the heat-transfer coefficient for each effect, the number of gallons of liquid to each effect per hour, and the percentage of solids in each liquor.

184. From the data of Prob. 183, calculate the B.P.R. in each effect. Assuming that the B.P.R. in the first effect is due to hydrostatic head only and that the depth of liquor is the same in each effect, determine the B.P.R. due to hydrostatic head and due to vapor pressure lowering by the concentration of solids in each effect.

185. From the data in Prob. 183, calculate the pounds of water evaporated in the system per pound of live steam used, the pounds of water evaporated in effects III and IV by flashing of the condensate, the self-evaporation in effects II, III, and IV. Note that condensate from the first effect was sent to the boiler house for use as feed water. It is, therefore, not included in the total condensate from IV.

CHAPTER V

DISTILLATION

Distillation is the term applied to the vaporization and subsequent condensation of a liquid for the purpose of separating two or more liquid *components* of an original solution into more or less pure *fractions* or portions. Its operation depends upon the fact that materials differ in their vapor pressures at a given temperature. Thus, when a solution or a mixture of two or more volatile substances is boiled, the vapor coming off has a greater proportion of the substance of high vapor pressure than the proportion of the same component in the original solution. Thus, since the *distillate* (material which has been vaporized and condensed) is richer in the more volatile component, the *residue* (liquid left in the still) is poorer in that same component. As distillation proceeds, the composition of the residue becomes progressively lower in the more volatile material and therefore richer in the higher boiling components. If the original charge in the still has only two components (*e.g.*, aniline and water), it is called a *binary* mixture; if there are three components, a *ternary* mixture (*e.g.*, phenol, water, and toluene), etc.

Classification.—Distillations are classified as *simple* and *fractional*. The former class involves merely vaporization and subsequent condensation of the vapor; the latter class involves vaporization, special handling of the vapor to separate it further into richer and poorer fractions, and final condensation of the enriched vapor, with return to the still of the fractions containing less of the highly volatile material than was in the original vapor. Both simple and fractional distillations may be carried out under vacuum, at atmospheric pressure, or at elevated pressures. When a very volatile liquid is to be separated from one which is relatively nonvolatile, the distillation is often called *stripping*.

VAPOR-PRESSURE RELATIONSHIPS

Vapor pressure, as previously discussed, is a property of every liquid (and solid), which depends upon temperature and composi-

tion. When a pure material is heated to such a temperature that its vapor pressure equals that of the surrounding space, further addition of heat causes the liquid to boil at constant temperature and to continue boiling as long as heat is supplied and the vapors can escape without causing the pressure above the liquid to increase. Table XX gives the temperature at which

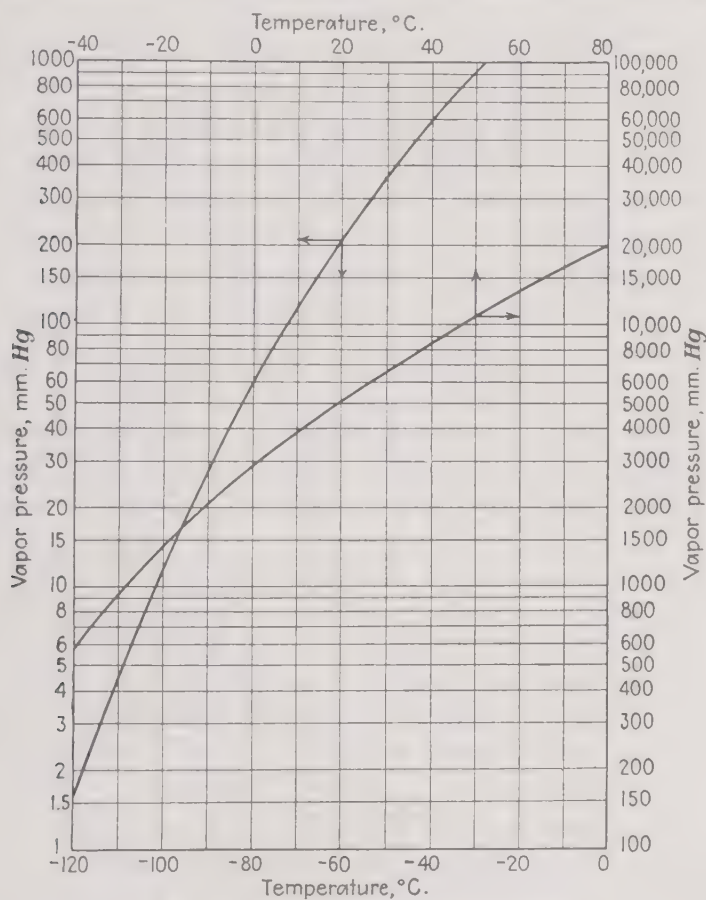


FIG. 21.—Vapor pressure of chlorine.

various pure substances have the indicated vapor pressure. Each temperature, therefore, is the boiling point of the pure material, if the pressure above the liquid corresponds to the indicated vapor pressure. The temperatures are given in degrees centigrade, the pressures in millimeters of mercury. Note that 1 in. = 25.4 mm.

Instead of tables, various types of curves are often used to present data on the vapor pressures of liquids. This allows the

vapor pressure of a given material at any temperature to be read without interpolating between the relatively few values that can be given in a table. Also, it permits the use of a few experimentally determined points to establish the temperature-vapor-pressure relationships over a wide range. Thus, in Figs. 21, 22, and 23, curves are given for the vapor pressures of water, sulphur,

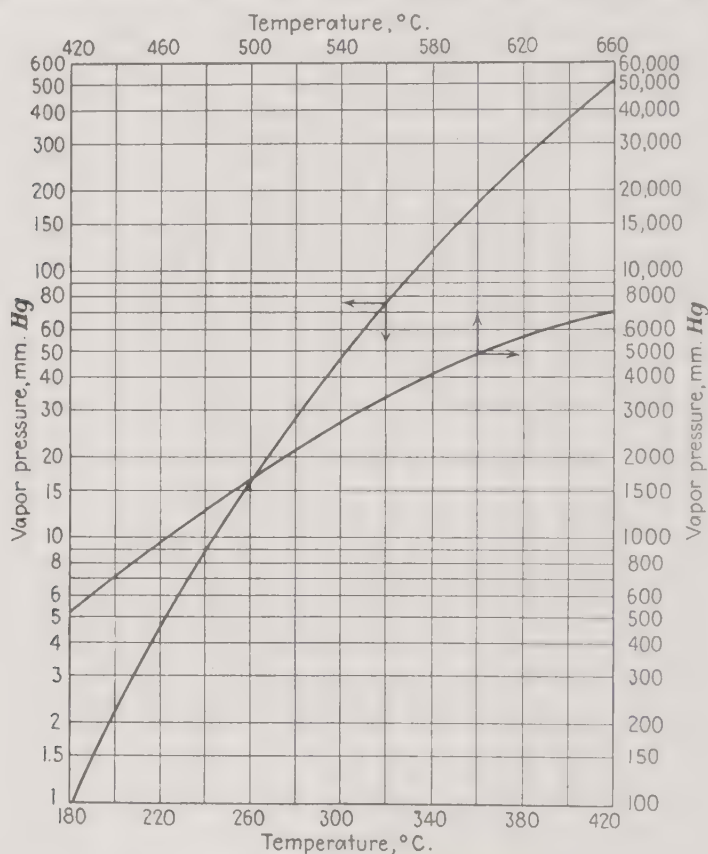


FIG. 22.—Vapor pressure of sulphur

and chlorine at various temperatures. These curves, therefore, show the boiling points of these pure materials for any pressures within the range of the chart.

Another useful method of giving such data is based upon Dühring's rule, illustrated by Figs. 24, 25, and 26. These have been prepared by plotting the temperature at which the liquid in question has a known vapor pressure against the temperature at which a standard liquid has the same vapor pressure. By suitable choice of the "standard liquid," a line drawn through

the plotted points will be straight. Then, by having an accurate table or curve for the vapor pressures of the standard over a wide range of temperature, the vapor pressure of any of the liquids at any desired temperature is obtained by reading from the chart the temperature at which the standard has the same pressure and then looking up that pressure on the curve or table for the standard. For the three figures given, chlorine is the standard for

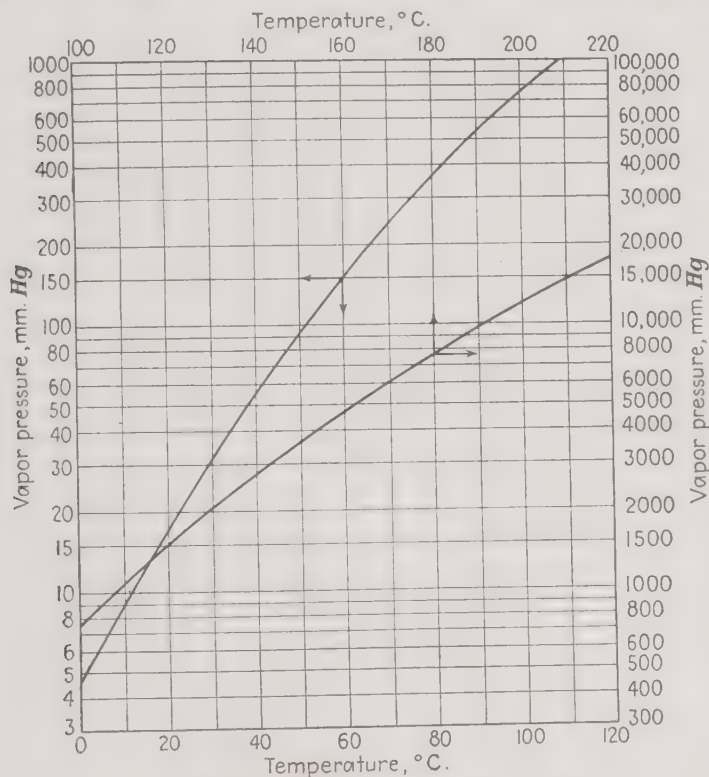


FIG. 23.—Vapor pressure of water.

one, sulphur for the second, and water for the third. Pressure-temperature curves for these reference standards are given, as already noted.

Vapor pressures of mixed liquids and of solutions are of great importance in distillation work, since the difference between the composition of a liquid mixture and of the mixed vapor above it determines the extent to which the components can be separated by distillation.

Immiscible liquids, completely or substantially insoluble in each other, have a vapor in which the partial pressure of each

TABLE XX.*—TEMPERATURE VS. VAPOR PRESSURE OF PURE SUBSTANCES

I. Very low boiling substances
(Millimeters of mercury-vapor pressure)

Temperature, °C.	Hydrogen (H ₂)	Nitrogen (N ₂)	Oxygen (O ₂)	Methane (CH ₄)	Ethylene (C ₂ H ₄)	Carbon monoxide (CO)	Carbon dioxide (CO ₂)
-260	33.75						
-250	1,622						
-220	.....	.....	0.92				
-210	.....	86	12.08				
-200	.....	429	79.9	.....	.....	249	
-180	.....	3,110	1,029	118.9	.....	2,030	
-150	.....	19,100	9,500	1,720	16.5	15,130	
-130	.....	.....	27,430	7,410	121		
-110	.....	.....	.....	.....	521	.....	34.6
Boiling point at 760 mm.	-252.6°C.	-195.7°C.	-182.8°C.	-161.4°C.	-103.9°C.	-191.5°C.	Solid

II. Substances boiling at moderate temperatures

Temperature, °C.	Ammonia (NH ₃)	Sulphur dioxide (SO ₂)	Ether [(C ₂ H ₅) ₂ O]	Acetone [(CH ₃) ₂ CO]	Methyl alcohol (CH ₃ OH)	Ethyl alcohol (C ₂ H ₅ OH)	Benzene (C ₆ H ₆)
-40	538.3	162.3	18.71	4.44	1.37	0.36	
-20	1,426.8	476.7	65.2	19.95	7.27	2.43	
0	3,221.0	1,190	185.0	65.0	29.3	11.69	
+20	6,428.5	2,508	437	180.3	95.2	43.8	74.8
+40	11,658	4,712	925	415.4	261.4	134.5	181.5
+60	.....	.....	1,740	856.1	625	352.9	388.0
+80	.....	.....	2,974	1,611	1,339	811	748
+100	.....	.....	4,855	2,797	2,621	1,684	1,335
Boiling point at 760 mm.	-33.4°C.	-10.0°C.	34.6°C.	56.5°C.	64.9°C.	78.3°C.	79.8°C.

III. Substances boiling at higher temperatures

Temperature, °C.	Toluene (C ₆ H ₅ CH ₃)	Phenol (C ₆ H ₅ OH)	p-Cresol (C ₆ H ₄ CH ₃ OH)	Nitrobenzene (C ₆ H ₅ NO ₂)	Naphthalene (C ₁₀ H ₈)	Glycerin (C ₃ H ₅ O ₃)	Mercury (Hg)
100	555	40	18.5	20.5	18.3	.....	0.28
130	1,265	143	71.9	70.3	60.6	1.47	1.20
180	.....	715	407	355	296.8	18.9	8.76
200	.....	1,194	735	596	495.2	43.4	17.22
230	.....	.....	.....	.....	965	130	42.83
260	.....	.....	.....	.....	.....	334	95.94
Boiling point at 760 mm.	110.6°C.	182.2°C.	201.1°C.	209.8°C.	218°C.	290°C.	357°C.

* Selected from extensive tables in "Einfache und Fraktionierte Destillation," by C. v. Rechenberg, Schimmel & Co., Miltitz bei Leipzig, 1923.

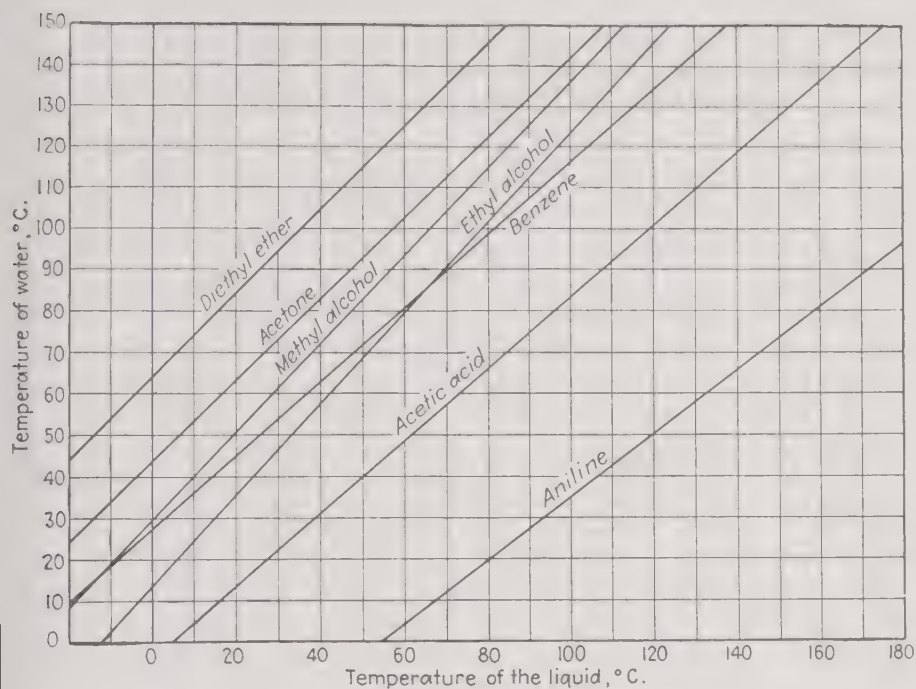


FIG. 24.—Dühring lines using water as reference standard.

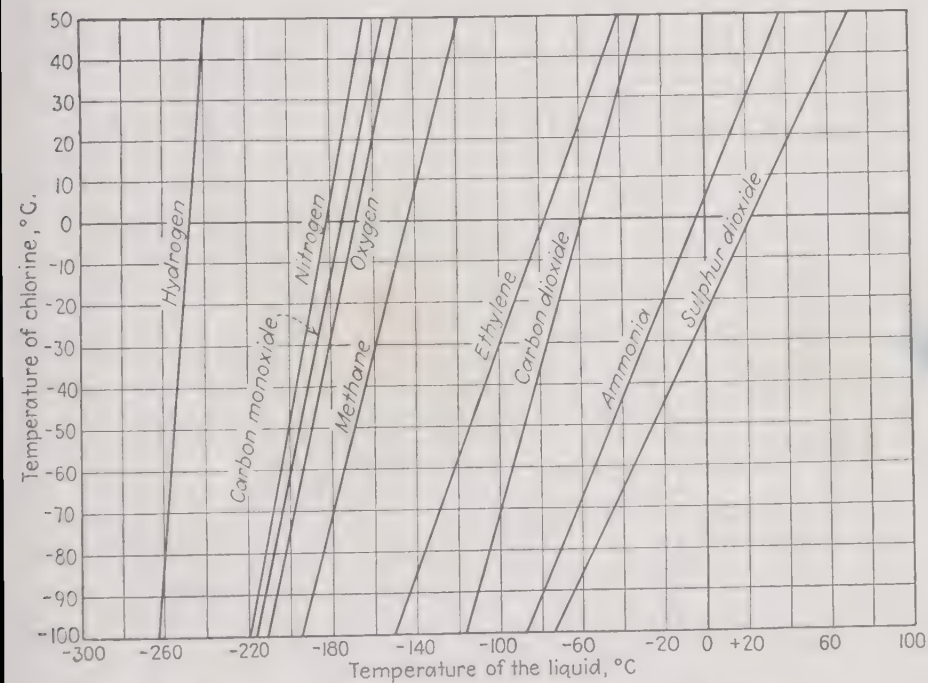


FIG. 25.—Dühring lines using chlorine as reference standard.

component is that for each pure material in the mixture. Thus, if glycerin and liquid mercury are in a still at $230^{\circ}\text{C}.$, the glycerin vapor above the liquid has a partial pressure of 130 mm. and the mercury has a partial pressure of 42.83 mm., just as though each component were present alone. The total pressure is, therefore, $130 + 42.8 = 172.8$ mm.; if the pressure on the still is reduced to that point, the mixture will boil. The vapor coming off will consist of 42.8 mols of mercury for every 130 mols of glycerin.

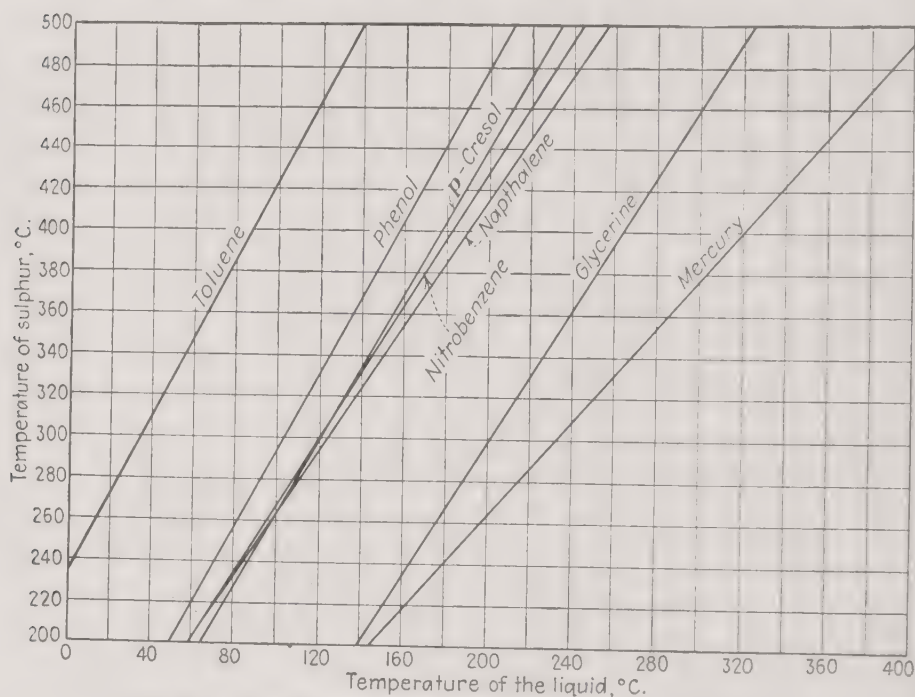


FIG. 26.—Dühring lines using sulphur as reference standard.

The relative proportions of the components in the still have no influence on the composition of the vapor as long as some of each is present. Since mercury (atomic weight 200.6) is a monatomic gas (*i.e.*, has a molecular formula of Hg as compared to diatomic molecules like O_2), there will be 42.8 mols or 8,586 lb. of mercury vaporized together with 130 mols or 11,973 lb. of glycerin (molecular weight 92.1).

Completely miscible liquids are generally encountered in most distillation work. They evolve vapors in which the partial pressure of each component is not the same as that which would exist over the pure material at the existing temperature. To

predict what separation can be effected by distilling vapors from such a mixture, therefore, it is necessary to know how each component's vapor pressure is affected by the presence of the other materials. In *most* cases, this cannot be predicted from the vapor-pressure curves of the pure components but must be determined by experiment or by reference to published data.

One method of presenting data on binary mixtures is illustrated by the three sets of curves in Figs. 27, 28, and 29, showing the boiling points at atmospheric pressure for three pairs of liquids. For a given composition, shown by the abscissa, the boiling

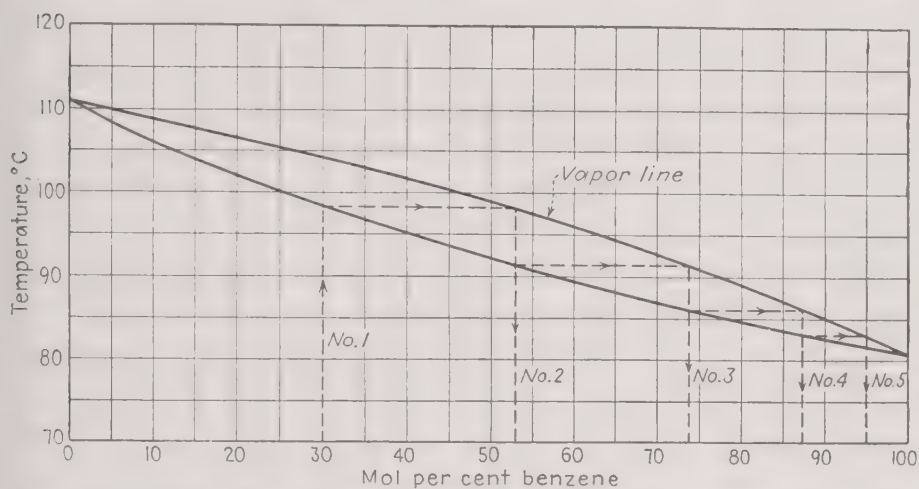


FIG. 27.—Boiling-point diagram (benzene-toluene), illustrating “normal” types of binary mixture.

point for that mixture is the ordinate of the curve. The composition of the vapor evolved from the liquid of this composition at the boiling point is given by the point on the “vapor curve” for that temperature.

The “normal” type of binary mixture gives a relation between liquid and vapor composition illustrated by the diagram for benzene and toluene (Fig. 27). For any mixture, the boiling point is found by moving vertically upward to the lower of the two curves, then horizontally to the left to read the boiling point in degrees centigrade. Thus, for 30 mol per cent benzene, the boiling point is found to be 98.5°C. By moving horizontally to the right on this line until the curve marked “vapor line” is reached and then moving vertically down to the base, the composition of vapor in equilibrium with the 30 mol per cent benzene

is found to be 53 mol per cent benzene and 47 mol per cent toluene. Except for pure toluene (0 per cent benzene) at the extreme left end and for pure benzene (100 per cent) at the extreme right, it

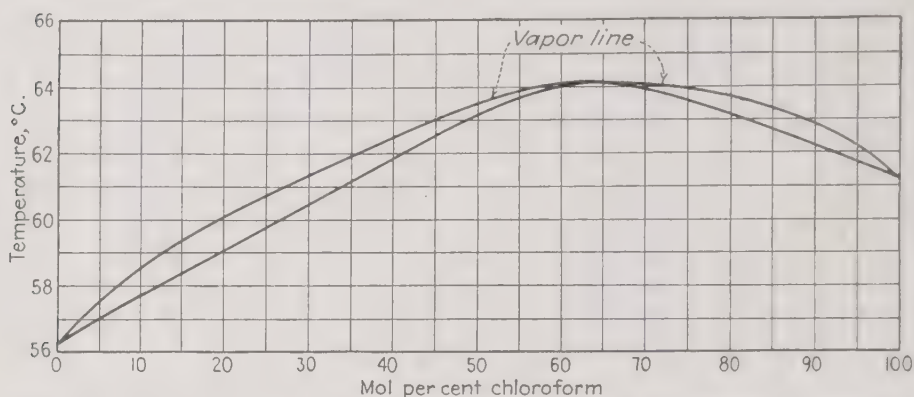


FIG. 28.—Boiling-point diagram (chloroform-acetone), illustrating “maximum boiling-point” type of binary mixture.

will be seen that the vapor always contains a higher per cent benzene than the liquid from which it is boiled off. This is expressed by saying that the vapor is “richer” in benzene.

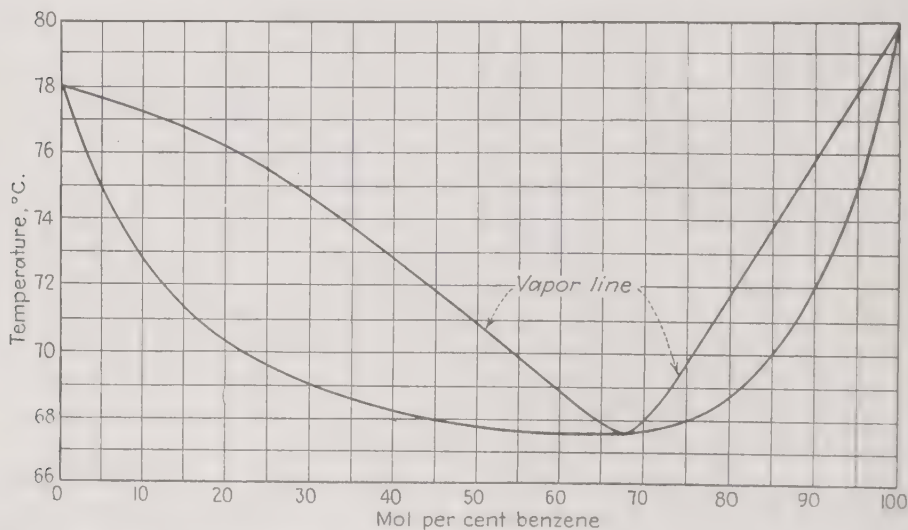


FIG. 29.—Boiling-point diagram (benzene-ethyl alcohol), illustrating “minimum boiling-point” type of binary mixture.

One of the other two diagrams (Fig. 28) illustrates mixtures having a *maximum boiling point* (e.g., chloroform and acetone), in which case a mixture of 62.5 mol per cent chloroform boils at 64.1°C., a temperature higher than either of the pure ingredients

and higher than any other mixture. From this *constant boiling mixture* (C.B.M.) a vapor of the same composition as the liquid is evolved. From any liquid mixture containing less than 62.5 per cent chloroform, the vapor is poorer in chloroform than the liquid from which it boils; from any liquid containing more chloroform than the C.B.M., the vapor is normal, *i.e.*, richer than the liquid.

The third diagram (Fig. 29) shows the curves for benzene and ethyl alcohol, illustrating the type of mixtures having a *minimum boiling point*. Here, liquids poorer than the C.B.M. have normal vapors; those richer than the C.B.M. give vapors poorer than themselves.

In some cases it is possible to calculate the vapor pressure of each component by the use of Raoult's law or Henry's law.

Raoult's law states that the partial pressure of a solvent in which a small amount of solute is dissolved is the vapor pressure of pure solvent multiplied by its mol fraction in the liquid. If P is the vapor pressure of pure solvent and x is the mol fraction of the pure solvent in the liquid, then p is the actual partial pressure of the solvent over the liquid. That is,

$$p = Px \quad (17)$$

For some pairs of liquids this law holds quite well for *all* concentrations; *e.g.*, pentane and heptane, benzene and chlorobenzene, and benzene and toluene. In other cases, such as hydrochloric acid and water, it does not hold at all.

Henry's law states that the partial pressure of a liquid (solute) dissolved in a relatively large amount of a solvent is a constant multiplied by the mol fraction of the liquid (solute) in the solution. That is,

$$p = Kx \quad (18)$$

As in the case of Raoult's law, this law can be used only for certain specific mixtures where it has been found to apply. Thus, Robinson¹ points out that the vapor pressure of ammonia over aqueous solutions can be calculated by Henry's law. At 25°C., the constant $K = 748$, the value of p being expressed in millimeters of mercury.

¹ ROBINSON, C. S., "The Elements of Fractional Distillation," 1st ed., p. 35, McGraw-Hill Book Company, Inc., New York, 1922.

STEAM DISTILLATION

To distill certain materials it is often convenient to use the principle already noted that materials insoluble in each other exert the same vapor pressure as if present alone. Thus, if benzene and water are heated, the mixture boils when the combined vapor pressures equal the pressure on the system, whether this is atmospheric or some lower pressure maintained by a vacuum pump. At $60^{\circ}\text{C}.$, for example, benzene has a vapor pressure of 388 mm. and water a pressure of 149 mm. so that the combined pressure would be $388 + 149 = 537$ mm. At this absolute pressure, then, the mixture would boil. If steam were continually introduced, part of it would condense, supplying the necessary latent heat to continue vaporizing the benzene, and the vapors coming off would have the same proportion (388 mols to 149 mols of steam) as long as the pressure was maintained at 537 mm. and as long as any benzene remained.

This principle is of especial advantage for very high-boiling materials which cannot be boiled alone with existing sources of heat. Thus, if naphthalene were to be distilled at $180^{\circ}\text{C}.$ by means of steam at $190^{\circ}\text{C}.$ and no source of vacuum were available, the temperature could be maintained at $180^{\circ}\text{C}.$ by means of steam coils, and live steam could be injected to effect the steam distillation. At this temperature, naphthalene has a vapor pressure of 297 mm. so that boiling would occur when the partial pressure of the live steam introduced made up the difference between the atmospheric pressure and that of the naphthalene, or $760 - 297 = 463$ mm. It is to be observed that no liquid water would exist in the still at this temperature ($180^{\circ}\text{C}.$) so that the partial pressure of the steam depends only upon the quantity of it that is introduced until the total combined pressure equals 760 mm., and that the vapors then pass off in the ratio of 297 mols of naphthalene for every 463 mols of steam introduced. Any other gas, insoluble in naphthalene, would act in the same manner, each mol acting the same as a mol of steam.

In the above example, if the total pressure above the liquid in the still were maintained at some lower pressure, *much less steam* would be required to carry out the distillation. Thus, if the pressure were 300 mm., only 3 mols of steam would be required for 297 mols of naphthalene vapor. From this obser-

vation, it is evident that steam distillation economy requires that the liquid be heated to the highest available temperature and that the pressure be kept as low as possible. The steam is usually superheated before introduction, so that it will not take heat away from the batch.

ENRICHMENT OF VAPORS

Redistillation.—From the curve in Fig. 27, showing the composition of the vapor given off at 98.5°C . in boiling a mixture of benzene and toluene at atmospheric pressure, it will be noted that from a charge containing 30 mol per cent benzene and 70 mol per cent toluene, the vapor will contain 53 mol per cent benzene and 47 mol per cent toluene. If this vapor were condensed and then brought up to boiling at 91.5°C ., a new vapor would be evolved having a composition of 74 per cent benzene and 26 per cent toluene, and the new residue would contain proportionately less benzene than when first condensed. By repeated condensations and re-evaporations a final product of substantially pure benzene could be obtained.

Partial Condensation.—A similar result can be obtained by condensing a very small amount of the vapor by slight cooling, drawing off this condensate, and cooling the vapor a little more, thus condensing another small amount of liquid containing a *relatively* large amount of toluene because this liquid must, if given sufficient time, be in equilibrium with the vapor at the temperature then existing.

Fractional Distillation.—If the vapors from 30 per cent benzene and 70 per cent toluene (molal percentages), boiling at 98.5°C ., are allowed to bubble into a liquid of the same composition as themselves (*i.e.*, 53 per cent benzene, 47 per cent toluene) which has been heated just to its boiling point (91.5°C .), they will condense, giving up their latent heat and thereby boiling off a new vapor containing 74 per cent benzene and 26 per cent toluene. At the same time, the liquid residue from this second still, now reduced in benzene content by the removal of the 74 per cent vapor, could be allowed to flow into the first still, thereby enriching it again toward the original 30 per cent benzene composition. Simultaneously, the 74 per cent vapor from the second still could be allowed to bubble into a third still containing 74 per cent benzene at its boiling point (86°C .), thereby evolving vapor

containing 87.5 per cent benzene and returning to the second still a liquid containing 74 per cent benzene. By such successive steps, supplying heat to the first still only, the vapor from each still in the series is progressively richer in benzene and poorer in toluene until substantially pure benzene passes from the last

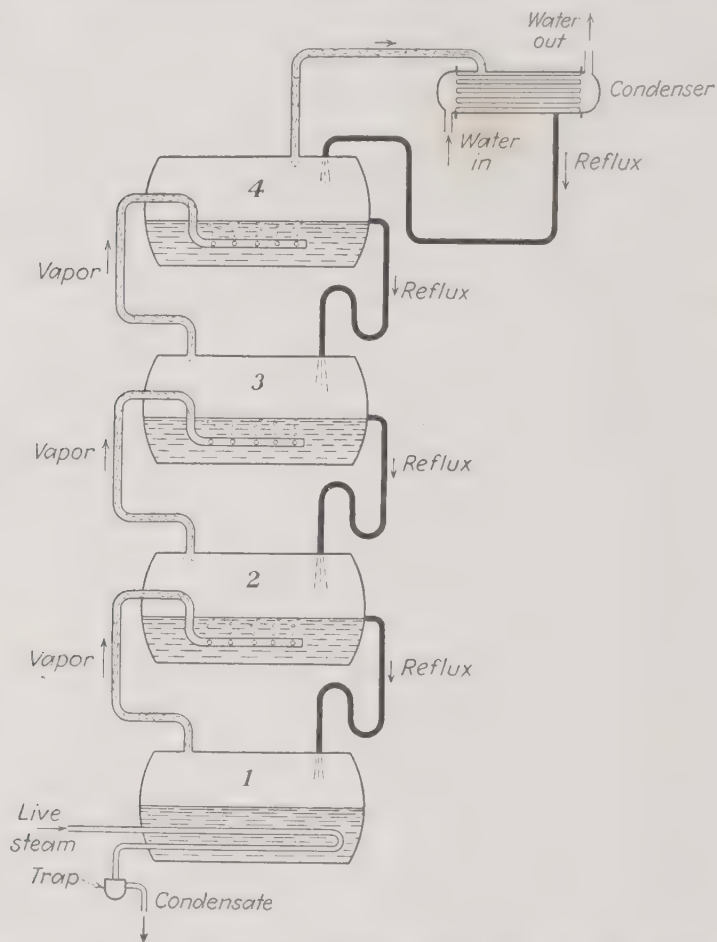


FIG. 30.—Fractionation by a series of stills; 100 per cent reflux.

still into a final condenser. If there has been no radiation loss from the series of stills, the amount of heat obtained by condensing this benzene will be exactly equal to that introduced in the coils of the first still. To maintain the exact conditions given, it would be necessary to return all of this condensed benzene to the last still so that the proper amount of liquid could flow back to the preceding still and so on down the line. Such a series of

operations is called "fractional distillation," obviously combining the methods of redistillation and of partial condensation. Figure 30 shows the operation diagrammatically.

For the theoretical case given above, certain factors are found to be essential:

(a) The vapors rising from each still must be in equilibrium with the liquid in that still, following the temperature and composition conditions given on the boiling-point diagram.

(b) The liquid flowing back into each still must equal in amount and composition the vapors coming into the still from which that liquid is flowing.

(c) There must be no addition or loss of heat in the system except the introduction of heat in the steam coils of the first still and the removal of exactly the same amount of heat in the final condenser.

Practical application of this method of vapor enrichment involves some modification of theory. Obviously, the purpose of such an operation is to take out as much pure benzene as possible. Therefore, all the condensate *cannot* be returned to the last still. However, by taking off a portion of the benzene (*forward flow*) and returning another portion (*reflux*), it is possible to make use of the process to effect the desired separation. The proportion of the vapor leaving the last still in the series which must be returned to keep the system functioning properly is called the *reflux ratio*. It may be stated as the per cent of total vapor returned (e.g., "80 per cent reflux," meaning that 80 per cent of the vapor entering the final condenser is returned as reflux and 20 per cent taken off as forward flow) or it may be given as pounds of reflux per pound of forward flow (e.g., 4:1, meaning that 4 lb. of condensate is returned for every pound taken off as product).

Instead of a series of stills, the process may be carried out by having a series of chambers or *plates*, one above the other, all erected above the original still pot. The vapor from the pot bubbles through the liquid on the first plate, the resulting vapor from that plate bubbles through the liquid on the second plate and so on, until the final vapor from the top of the column passes to a condenser. As this is going on, reflux from the condenser is flowing into the first plate, and after the partial condensation and reboiling of that section the reflux from that plate is con-

tinually flowing down to the next and so on down until the final reflux from the bottom plate returns to the still pot.

In a batch distillation, the continued removal of the low-boiling component (*e.g.*, benzene in the case of our illustrative example) causes the still-pot liquid to become continually lower in benzene content. Its boiling point rises correspondingly, the vapor coming from it contains less and less benzene, and this effect is carried progressively up the column until finally the vapor coming to the condenser is no longer pure enough benzene to meet specifications. The forward flow is then diverted into another receiver and fractionation continued until practically pure toluene is coming from the condenser. The toluene in the column is then allowed to drain back into the still pot, which is discharged into a toluene receiving tank. The "intermediate" fraction or *cut* is then recharged to the still pot, along with a fresh batch of the original mixture and another distillation can be started.

Because of the fact that complete equilibrium is not established on any actual plate and because part of the product is continually withdrawn, the number of actual plates in a column is always greater than that required for the theoretical conditions considered in the beginning of this discussion. The ratio of the fractionation actually accomplished by a plate to that calculated for a "theoretical" plate is called the *plate efficiency*. This is generally about 50 to 60 per cent of theory. By calculation, it can be shown that the number of theoretical plates required for a given separation *increases* as the reflux ratio *decreases* so that an economic balance must be made between the investment cost for additional plates and the operating cost for additional steam to perform a desired separation. There is, however, a minimum reflux ratio for any separation, below which even an infinite number of plates will not give the desired product.

Instead of batch operation, a fractionating column may be operated continuously, fresh feed being introduced at some plate having approximately the composition of the feed. In this case, the portion of the column below the feed is engaged in fractionating out all of the low-boiling component (*e.g.*, benzene) so that the liquid in the still pot is substantially pure toluene. It is thus possible to feed the mixed liquid at an intermediate plate, taking off pure benzene from the top of the column as

forward flow and pure toluene from the still pot as *bottoms*. In this way, no intermediate cut is produced, and the temperature and composition of liquid and vapor at each point in the column are constant. The plates below the feed are often spoken of as the *stripping section* and those above it as the *rectifying section*.

EQUIPMENT

The equipment used in distillation operations is selected in accordance with the extent of separation required, the scale of operation, available heating means, and various other factors peculiar to the problem involved. Individual items may be discussed according to their place in the "flow sheet" of vaporization, fractionation, stripping, condensation, and handling of condensate and noncondensable gas.

VAPORIZATION

Still Pots.—These may be vertical kettles, with or without agitators, or horizontal tanks, as discussed under Evaporation. Kettles are often used where the distillation follows a chemical reaction, after which solvent is to be removed without transfer of the batch. The limitations on disengaging area to avoid foaming or entrainment are of the same importance as in the case of similar units for evaporation of water. Heating by jackets, especially on relatively high-boiling liquids, may limit the distillation rate but disengaging velocity is still of considerable importance. Disengaging rates of 40 to 60 lb. of toluene per square foot per hour have been obtained, indicating that the molecular weight of the vapor enters into the determination of this factor. That surface tension is also important has been shown by rates of 80 lb. per square foot per hour for boiling capryl alcohol, a material of low surface tension. Unless specific data are available, however, it will be assumed that organic vapors may be taken off without appreciable entrainment at a rate of 0.5 lb. mol per square foot per hour, irrespective of pressure or vacuum.

Heating may be done by various means. Formerly, all high-temperature distillations required direct firing of still pots. For petroleum, the stills were 10 to 14 ft. in diameter and 30 to 40 ft. in length. Accumulation of coke or solids along the bottom acted as insulation and caused overheating of the bottom plates,

necessitating extra heavy bottoms and frequent replacement. As an approximation, it was assumed that the safe rate of heat transfer by direct firing was about 3500 to 4000 B.t.u. per square foot per hour. For distillations at temperatures requiring direct fire, the present practice is to use, instead of still pots, pipe stills, to be discussed later. However, for liquids distilling at moderate temperatures, horizontal stills are heated by jackets or internal coils carrying steam, Dowtherm, or hot oil.

Another satisfactory method is to circulate the batch by pump or by natural convection through an external tubular heater.

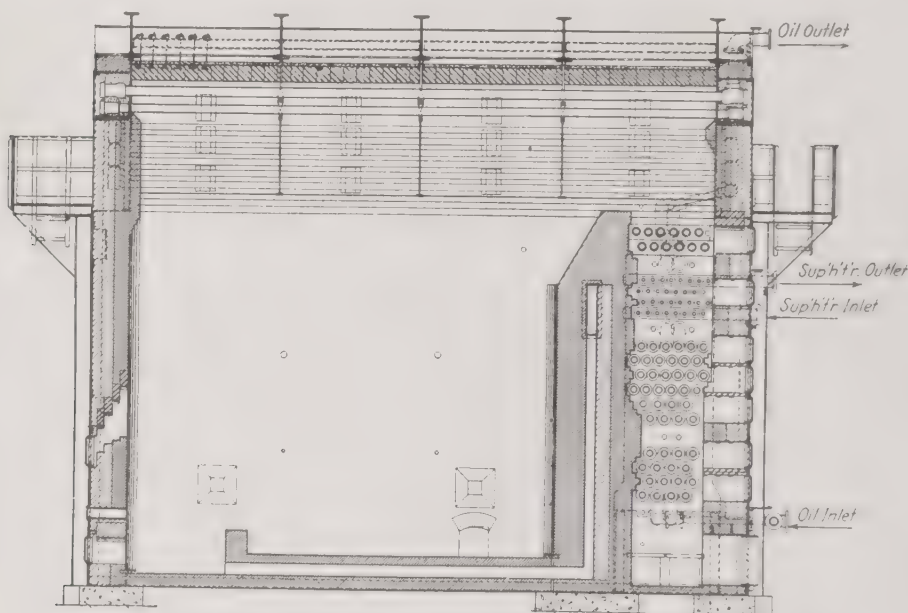


FIG. 31.—Pipe-still furnace. (Courtesy of Foster Wheeler Corporation.)

In this way, higher velocities can be obtained than are possible in the body of the still itself, and heat-transfer rates are thus increased very greatly. Another advantage of the external heater is that the circulating mass of liquid and foam may discharge into the free area of the still, above the liquid level, so that disengagement takes place from the relatively enormous surface of the drops of liquid. This permits very much higher distillation rates than are obtainable when disengagement takes place from the main liquid surface. These external exchangers may be heated by steam or Dowtherm around the tubes or even by direct fire.

In case live steam is to be introduced into the batch, a perforated "sparger" pipe is generally used. The total area of the perforations should be somewhat less than the cross-sectional area of the pipe so that even distribution of the steam may be obtained. The area needed to deliver a given quantity of steam will be discussed in a later section under Fluid Flow.

Pipe Stills.—As a means of vaporizing large quantities of liquids, especially at elevated temperatures, this type of vaporizer has come into extensive use. As the name implies, the unit consists of a series of pipes or tubes through which the charge is pumped at high velocity, heating being done by hot gases around the tubes. Part of the tubes are placed in the "radiant" section of the furnace and others, often with extended surface fins to increase the area for heat transfer, are placed in the path of the gases that have passed the bridge wall from the combustion chamber and are therefore in the "convection" portion of the unit. Countercurrent flow of the charge permits economical recovery of the heat from the combustion gases. Because of the large amount of heat absorbed by the brick furnace setting, pipe stills are not economical for batch operation but are very well adapted to continuous distillations, such as are the rule in the petroleum industry. Figure 31 is a cross section showing some details of a modern pipe-still installation.

FRACTIONATION

Partial Condensers.—Although it is theoretically possible to effect a very complete separation of the components of a vapor by differential condensation, no practical means of accomplishing this have been developed. In some cases, where the vapor is very much richer than the liquid from which it is evolved, sufficient further enrichment may be secured by passing the vapors through vertical tubes surrounded by cooling water at a slightly lower temperature than the equilibrium temperature of the vapor, allowing the condensate with its higher percentage of high-boiling component to flow back to the still and the remaining vapor to pass up and out to a final condenser. It has been shown by calculation and experiment that such a condenser is equivalent to less than one "theoretical plate" of a fractionating column so that its use is exceedingly limited.

Sieve Plate Columns.—This type of fractionating column, shown in Fig. 32, is made up of a series of horizontal, perforated plates assembled at definite intervals in a cylindrical column. Vapors, passing through the perforations of each plate, bubble through the liquid on that plate and then pass on through the next plate above. Reflux flows from each plate through a *down pipe*, which extends a short distance (1 to 2 in.) above the plate and down below the liquid surface of the plate below. When the column is started, vapors pass up through the empty column, liquefying in the condenser. The condensate, unable to flow

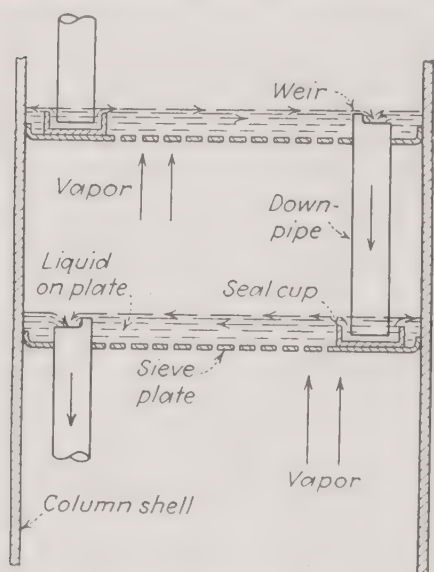


FIG. 32.—Sieve-plate column.

down through the perforations against the rising vapor, builds up on the top plate until it overflows the *weir* or rim of the down pipe from that plate. As it flows down the relatively large area of the down pipe, it seals the next plate in the same manner until finally all plates in the column are sealed. As long as the vapor velocity in the column is sufficient to prevent the reflux from flowing down through the perforations, the fractionation proceeds satisfactorily. The total area of the perforations is 7 to 10 per

cent of the cross-sectional area of the plate, the diameter of each hole being $\frac{3}{16}$ to $\frac{1}{4}$ in. Plates are usually spaced 12 to 18 in. apart.

This type of column is relatively inexpensive and works very well within a limited range of vapor velocity. If the vapor supply is increased beyond normal, the velocity through the perforations becomes excessive, causing back pressure which prevents liquor flowing down the down pipes fast enough to avoid *loading* of liquid at some point. When this occurs, the column "puke," discharging both liquid and vapor out through the condenser. On the other hand, if the rate of vapor flow decreases enough to permit the liquid on the plates to flow through, the plates empty themselves down the column, and

fractionation decreases very sharply. It is, therefore, exceedingly important that the vapor rate be held within rather narrow limits, a good measure of operation being a manometer at the base of the column which shows the total differential of pressure between top and bottom. Once the optimum differential has been found, the column should be operated at a carefully controlled rate of heat supply to maintain that differential pressure.

It is to be noted that the pressure drop from one plate to another is the result of three factors: pressure required to force the vapor through the perforations; head of liquid on the plate, which is the height of the down-pipe weir above the plate; and additional head of liquid due to the restricting influence of the weir on the liquid trying to flow into the down pipe. If the sum of these pressure drops equals the weight of a column of liquid in the down pipe from the liquid surface of the lower plate to the top of that down pipe, no liquid can flow down and the column will load.

Bubble Plate Columns.—This type of construction, shown in Fig. 33, is most widely used for fractionation. Each plate, spaced as noted for the sieve plate column, is provided with a down pipe as previously described. Instead of perforations, however, vertical *chimneys*, covered by inverted *caps*, provide for vapor flow. The lower edges of the caps are brought down close enough to the plate to be sealed by liquid before it can overflow the weir of the down pipe on that plate. Thus, the vapors rise in the chimneys, pass down the annular spaces between the chimneys and the caps which cover them, and bubble out through the liquid. To avoid large bubbles or unequal bubbling at points slightly higher than others, the edges of the caps are usually serrated or grooved. The cross-sectional area of the chimneys is usually about 11 to 12 per cent of the total area of the plate. A small drain hole in each plate permits the liquid in the column to drain out slowly after a shutdown but is too small to cause appreciable leakage in normal operation.

The vapor velocity in the free area of the column, between plates, is normally 1.5 to 2.0 ft. per second at atmospheric pressure, 4 to 5 ft. per second under vacuum, and 0.2 to 0.3 ft. per second at pressures of several atmospheres. However, since the sealing of the plates does not depend upon high velocity of vapor, this type of column can be operated at very low rates

when desired. Its upper rate is that at which loading occurs because the back pressure between plates has increased to a point at which the liquid reflux cannot flow down as fast as received from the plate above.

From what has been said about entrainment at disengaging velocities much lower than those in the sieve plate or bubbler

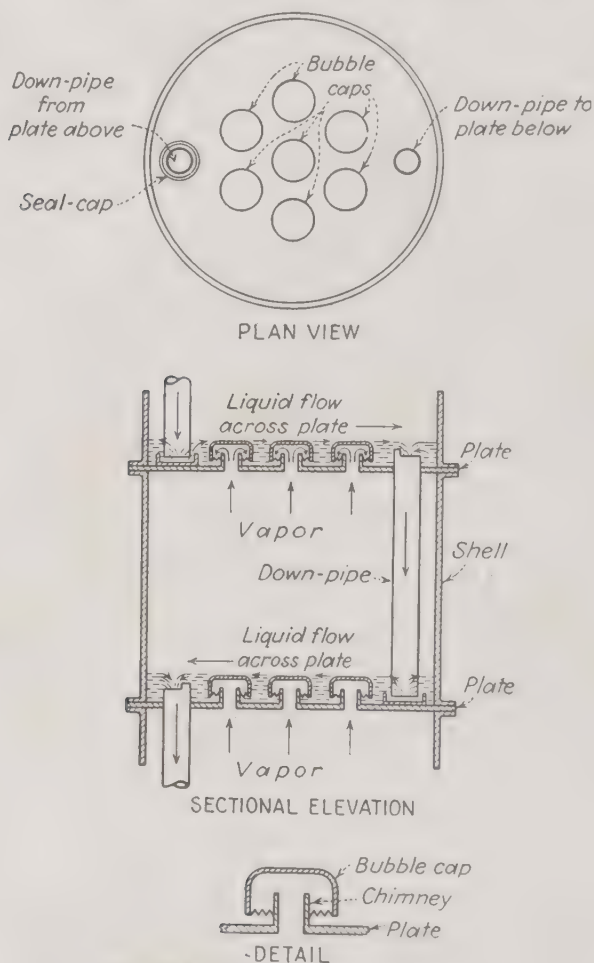


FIG. 33.—Bubble-plate column.

column, it is evident that some liquid must be carried as spray from one plate to the next. This occurs, but since its effect is only to change the liquid composition of the next plate by a small amount, the high rates are permissible in columns whereas they represent loss of valuable material in "straight-lead" evaporations or distillations. In some cases, however, where a

highly colored material from the bottoms may be carried up from plate to plate and affect the color of the product, special baffles or "spray eliminators" are placed below each plate to permit drops of entrained liquid to coalesce and flow back into the liquid below.

Figure 34 shows a Semi-Works unit, consisting of a still pot, column, condenser, and various accessories. When the column is by-passed, "simple" distillations can be made. With the column, batch or continuous fractionations are made, with or without vacuum.

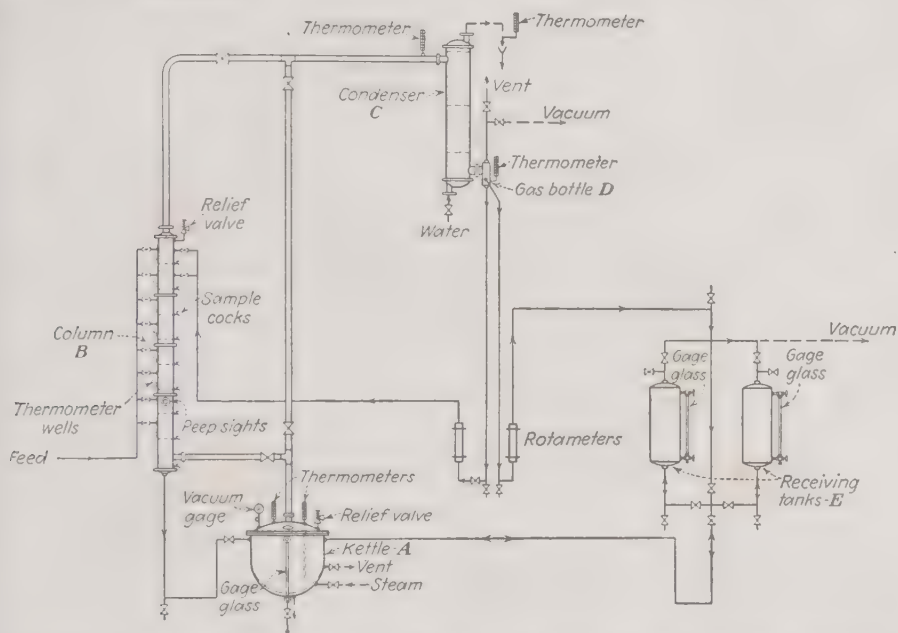


FIG. 34.—Experimental distillation unit. (Courtesy of the Lummus Company.)

Packed Columns.—For small-scale operations, where the expense of sieve plate or bubble cap columns is not warranted, fractionation may be obtained by means of a tower filled with packing material having a large exposed surface for interaction of vapor and reflux. Packing materials include small cylinders of glass, stoneware, or carbon (Raschig rings), curved stoneware pieces (Berl saddles), as well as jack chain, wire helices, and a variety of other specially shaped objects. The packing must be supported by suitable means at the base of the column, a cone-shaped support of heavy rods being quite satisfactory. A flat perforated plate support is to be avoided because the packing

tends to obstruct the holes and cause excessive back pressure at this point.

Since the packed column has no actual plates, it is customary to speak of the *height of equivalent theoretical plate* (H.E.T.P.) for a given type of packing in a specified diameter column. The actual height of packing in feet is divided by the number of theoretical plates indicated by the fractionation obtained experimentally on the type of column under consideration. That is, if a 4-in.-diameter column, packed with $\frac{1}{4}$ -in.-diameter Raschig rings to a height of 6 ft., is found to perform the fractionation of a mixture of benzene and toluene as completely as calculated for 12 theoretical plates, the H.E.T.P. of the column is said to be 6 in. Columns larger than 6 or 8 in. in diameter are not very efficient, giving values of H.E.T.P. of several feet, so that the use of this type of equipment has been limited mainly to Semi-Works and laboratory distillations.

The vapor velocities, calculated as though no packing were present, are generally in the range of 1.0 to 1.5 ft. per second. As in the case of sieve plate columns, packed towers must be operated at a definite velocity, high enough to ensure interaction of liquid and vapor but not high enough to cause loading. A manometer showing the difference in pressure between the bottom and the top of the column is a necessity for good operation.

CONDENSATION

Coil or Pipe.—For small-scale operations, it is often sufficient to provide a coil submerged in cooling water or a jacketed pipe with cooling water flowing through the jacket. Formerly, it was common in the petroleum industry to use large water boxes through which the vapor pipes passed and delivered the condensate to receiving tanks.

Tubular Condensers.—Practically all units of commercial size utilize tubular condensers. Unless there are special reasons for passing the vapors through the tubes, it is desirable to pump the cooling water through the tubes, using the multipass system, so that the h_c on the water film is improved by good velocity. Vapors condensing on the outside of the tubes flow out at the discharge end into a flow box, from which noncondensable gases are vented to the air or pass to a vacuum pump, according to the type of operation.

ACCESSORIES

Vacuum pumps and vacuum jets are used in distillation practice, as they are in evaporator practice. For distillation work, however, it is usually much more important to obtain very low absolute pressures than it is in evaporation problems. Three-stage and even two-stage vacuum jets are now available to maintain pressures at 1 to 2 mm. The success of their operation follows the principles discussed previously under Evaporation.

Gravity separation of condensate into two liquid layers is sometimes necessary, one layer (*e.g.*, water) being drawn off and the other layer returned as reflux. The principles involved in continuous separators are discussed on page 197.

Heat exchangers are frequently used on continuous stills, the cold feed being preheated by countercurrent flow in exchangers carrying the hot products away from the column. Considerable heat economy is obtained by this means, as well as a saving of water that might otherwise be needed to cool the products.

CALCULATIONS

Assumptions.—In solving problems, the following assumptions may be made:

1. *Latent Heats.*—Assume that the latent heat of each component of a mixed vapor is the same as that of the component in the pure state at atmospheric pressure. This, of course, is not correct but must be assumed because complete tables of latent heats, etc. are not usually available. When water is vaporized, however, take the exact latent heat for water at the temperature of vaporization from the steam tables.

2. *Specific Heats.*—For a mixed liquid, calculate each component separately on the basis of the specific heat of the pure material.

3. *Volumes.*—Calculate volumes on the basis of the Law of Perfect Gases. Since these vapors are generally quite close to the boiling points of the liquids, an error is introduced, but the results will be adequate for problem use.

4. *Hydrostatic Head.*—The increase in boiling point of a liquid due to hydrostatic head is assumed to be that corresponding to an additional pressure of 50 per cent of the liquid head in the still. That is, if the absolute pressure in a still is 5 mm. and the

liquid is 4 ft. deep, the average pressure is taken as 5 mm. plus the weight of a column of liquid 1 sq. in. in cross section and 2 ft. deep, this weight being expressed as millimeters of mercury. The temperature of the boiling liquid is then assumed to be that corresponding to this average pressure.

Steam Distillations.—In calculating the vapors evolved in steam distillation or in any case where two substantially immiscible liquids are boiled, the following formula is used. Let W_A be the pounds of component A whose vapor pressure at the given temperature is P_A and let W_B be the pounds of component B , whose vapor pressure at the given temperature is P_B . Let M_A and M_B represent the molecular weights of each of the pure components in the vapor state. Then

$$\frac{W_A}{W_B} = \frac{P_A M_A}{P_B M_B} \quad (19)$$

Also note that if the total pressure of the system when boiling occurs is P ,

$$\begin{aligned} P &= P_A + P_B \\ P_A &= P - P_B \\ P_B &= P - P_A \end{aligned}$$

Fractionating Columns.—Since the total heat entering the bottom plate in a column is all assumed to be present in the final vapor from the top and since the weight of all material entering the bottom must be equal to the weight leaving in the forward flow plus that of the reflux from the bottom of the column, many calculations can be based entirely on heat and on weight balances.

ILLUSTRATIVE PROBLEMS

Illustration 1.—Glycerin is steam-distilled at 182°C. under a 26-in. vacuum. A test shows a steam consumption of 1.0 lb. per pound of glycerin distilled. What per cent excess steam, referred to that theoretically needed, is actually used?

From the Dühring line for glycerin in Fig. 26 it is found that glycerin has the same vapor pressure at 182°C. as the standard material (sulphur) has at 270°C. By reference to the vapor-pressure-temperature curve for sulphur, it is found that its vapor pressure is 21 mm. at 270°C. This means, therefore, that the vapor pressure of glycerin at 182°C. is 21 mm.

The total pressure on the distilling liquid is found from the vacuum reading (26 in. of mercury vacuum) as

$$\begin{aligned} 29.9 - 26.0 &= 3.9 \text{ in. of mercury absolute pressure} \\ 3.9 \times 25.4 &= 99 \text{ mm. of mercury absolute pressure} \end{aligned}$$

Since the steam must supply enough pressure to make up the difference between the partial pressure exerted by the glycerin and the total of the system,

$$99 - 21 = 78 \text{ mm., partial pressure of steam}$$

By equation (19), representing steam as *A* and glycerin as *B*,

$$\frac{W_A}{W_B} = \frac{P_A M_A}{P_B M_B}$$

Noting that the molecular weight of water is 18 and that the molecular weight of glycerin is 92,

$$\frac{W_A}{W_B} = \frac{78 \times 18}{21 \times 92} = 0.727 \text{ lb. of steam per lb.}$$

of glycerin, theoretically needed

The excess steam is found by subtracting the theoretical amount from the actual consumption.

$$1.00 - 0.727 = 0.273 \text{ lb. of steam per lb.}$$

of glycerin, excess over theory

$$\therefore \frac{0.273 \times 100}{0.727} = 37.5\% \text{ excess steam used}$$

Illustration 2.—A continuous fractionating column receives 10 mols of vapor per hour, which is being evolved from a solution containing 10 mol per cent benzene and 90 mol per cent toluene. The liquid returned from the bottom plate of the column is 15 mol per cent benzene. The reflux ratio for the distillation is 90 per cent. Assume constant latent heat per mol of any mixture of benzene and toluene. Calculate:

- (a) Composition of the forward flow from the condenser.
- (b) Pounds of forward flow per hour.
- (c) Composition of liquid on the second plate of the column.
- (d) Composition of vapor from the second plate.

(a) Neglecting any radiation losses, the heat in the vapor entering the column is still present in the vapor going to the condenser at the top of the column. Therefore, since the molal latent heats are assumed constant, the same number of total mols of vapor enter and leave each plate per hour. Likewise, the number of total mols of reflux entering the top plate of the column must equal the number of total mols of reflux from the bottom plate of the column back to the still pot.

The vapor entering the first plate (bottom) of the column is in equilibrium with a boiling liquid containing 10 mol per cent benzene and 90 mol per cent toluene, according to the data given. From the boiling-point-composition diagram for benzene and toluene (Fig. 27), it is found that this vapor is 22.5 per cent benzene. Since there are 10 mols of this vapor per hour,

$$10 \times 0.225 = 2.25 \text{ mols of benzene enter column per hr}$$

$$10 - 2.25 = 7.75 \text{ mols of toluene enter column per hr.}$$

The reflux ratio is 90 per cent. This shows that the number of mols of liquid returned from any plate is 90 per cent of the mols of vapor entering that plate.

$$10 \times 0.90 = 9.0 \text{ mols reflux from any plate}$$

Since the composition of the run-back from the column to the still pot is given as 15 mol per cent benzene,

$$9.0 \times 0.15 = 1.35 \text{ mols of benzene run-back from the bottom plate}$$

$$9.0 - 1.35 = 7.65 \text{ mols of toluene in this run-back}$$

All the benzene entering the system is that in the vapor from the still and all that leaves is in the forward flow and in the run-back from the column. Then the difference between benzene in the entering vapor and benzene in the run-back to the still must equal benzene in the forward flow.

$$\therefore 2.25 - 1.35 = 0.90 \text{ mols of benzene per hr. in forward flow}$$

The same reasoning applies to the toluene,

$$\therefore 7.75 - 7.65 = 0.10 \text{ mols of toluene per hr. in forward flow}$$

The forward flow must then be

$$0.90 \text{ mol of benzene} + 0.10 \text{ mol of toluene} = 1.0 \text{ mol of total vapor}$$

$$\therefore \text{Forward flow is } 90\% \text{ benzene, } 10\% \text{ toluene}$$

Since the total vapor entering the column is 10 mols per hour and since the reflux ratio of 90 per cent means that 10 per cent or 1.0 mol is taken forward, the forward flow, as calculated, is checked as correct.

(b) To calculate the weight of forward flow per hour, the number of mols of each component is multiplied by the respective molecular weight. Then,

$$\begin{aligned} 0.90 \times 78 &= 70.2 \text{ lb. of benzene per hr. in forward flow} \\ 0.10 \times 92 &= \underline{9.2 \text{ lb. of toluene per hr. in forward flow}} \\ &79.4 \text{ lb., total forward flow per hr.} \end{aligned}$$

(c) To determine the liquid composition on the second plate, counting the bottom plate as the first, the procedure is similar to that in (a). The liquid on the first plate, as shown by the run-back to the still pot, is 15 mol per cent benzene. From Fig. 27, the vapor in equilibrium with this is 31 mol per cent benzene. Since 10 mols of vapor of this composition leave the first and enter the second plate hourly,

$$\begin{aligned} 10 \times 0.31 &= 3.1 \text{ mols of benzene vapor enter second plate per hr.} \\ 10 - 3.1 &= 6.9 \text{ mols of toluene vapor enter second plate per hr.} \end{aligned}$$

As was shown before, the run-back from the second plate must contain as much benzene as the vapor that enters the plate minus the benzene leaving the system in the forward flow. Otherwise, benzene would be accumulating somewhere in the system, a condition that cannot exist in a truly continuous, balanced system. Then, subtracting the benzene leaving per hour in the forward flow from that entering the second plate as vapor,

$$\begin{aligned} 3.1 - 0.90 &= 2.2 \text{ mols of benzene in reflux from second plate} \\ 9.0 - 2.2 &= 6.8 \text{ mols of toluene in this reflux} \\ \therefore \frac{2.2}{9.0} \times 100 &= 24.4 \text{ mol \% benzene on second plate} \\ 100 - 24.4 &= 75.6 \text{ mol \% toluene on second plate} \end{aligned}$$

(d) The composition of vapor rising from the second plate must be in equilibrium with liquid of the composition determined in (c). Reference to the boiling-point-composition diagram shows that the vapor would be 45 mol per cent benzene.

By following the procedure as given in this illustration, the vapor from each plate can be calculated on up the column until a vapor is found which is approximately the same as that desired as forward flow. The number of theoretical plates, thus determined, divided by the expected plate efficiency (*e.g.*, 50 per cent) gives the actual number of plates required at the given reflux ratio. For any other reflux ratio, a new calculation must be made in the same way.

Instead of the tedious procedure required by this method, column designers use the McCabe-Thiele diagram.¹ However, the method already given permits a clear understanding of what takes place on a "theoretical plate" and is given here as better suited to the requirements of the present study.

Problems

186. Calculate the vapor pressure in pounds per square inch of the following and give the temperature in degrees Fahrenheit:

Hydrogen at -250°C .

Oxygen at -130°C .

Ammonia at 40°C .

Phenol at 200°C .

Naphthalene at 180°C .

187. Express in inches of mercury the vacuum in stills containing the following boiling liquids, assuming atmospheric pressure to be 29.9 in. of mercury:

Hydrogen at -260°C .

Methane at -180°C .

Sulphur dioxide at -40°C .

Nitrobenzene at 100°C .

Glycerin at 180°C .

Mercury at 180°C .

188. Using the Dühring rule charts, give the vapor pressures in pounds per square inch of the following:

Acetone at 98°C .

Acetic acid at 130°C .

Phenol at 150°C .

Glycerin at 300°C .

Carbon dioxide at -100°C .

Methane at -175°C .

¹ See Walter L. Badger and Warren L. McCabe, "Elements of Chemical Engineering," McGraw-Hill Book Company, Inc., New York, 1936.

189. A mercury manometer containing 0.1 lb. of mercury is accidentally emptied into a still containing glycerin at 230°C. Vacuum is applied until the mercury is distilled out by the glycerin. How many pounds of glycerin come over with the mercury into the condenser?

190. From a still containing 234 lb. of benzene (C_6H_6) and 644 lb. of toluene ($C_6H_5CH_3$) distillation is carried out until the boiling point of the residue has risen to 100°C. Assume that the resultant distillate has a composition midway between that of the first and that of the last vapor coming off. Calculate the pounds of C_6H_6 and of $C_6H_5CH_3$ in the distillate and in the residue. (Let X = mols of C_6H_6 in distillate.)

191. If a mixture of 50 mol per cent chloroform and 50 mol per cent acetone is distilled and the distillate and residue are redistilled, etc., until two products are finally obtained, each of which gives vapor of the same composition as the liquid, what are these two products?

192. A mixture containing 75 mol per cent chloroform and 25 mol per cent acetone is subjected to repeated redistillations as in Prob. 191. What are the two products finally obtained?

193. Using Raoult's law, calculate the partial pressure of benzene over a benzene-toluene mixture containing 50 mol per cent benzene at 20°C. Express the result in millimeters of mercury.

194. Using Henry's law, calculate the vapor pressure of ammonia (NH_3) over a solution containing 17 lb. of NH_3 in 162 lb. of water at 25°C.

195. If naphthalene were to be steam-distilled at a temperature of 200°C. and atmospheric pressure, how many pound mols of steam would be needed per mol of naphthalene? How many pounds per pound?

196. From a still maintained at a 30 mol per cent benzene—70 mol per cent toluene mixture, vapor is to be fractionated in a column to give a product containing 75 mol per cent benzene at the rate of 32.6 lb. of forward flow per hour. If an 80 per cent reflux is used, how many theoretical plates are needed? Assume that the heat of vaporization of one mol of any mixture of benzene and toluene is 13,700 B.t.u. and that no heat is lost from the column. How many B.t.u. per hour are used in the still for vaporization?

197. Recalculate Prob. 196 on the basis of 60 per cent reflux.

198. A continuous benzene-toluene stripping column is delivering 100 lb. mols of vapor per hour to a rectifying column, receiving a liquid of 12.5 mol per cent benzene from the bottom plate of the latter. The final product is 99 mol per cent benzene, taken off at a reflux ratio of 9:1. What is the composition of the reflux to the bottom plate of the rectifying column?

199. For the rectifying column of Prob. 198 calculate the diameter of the column to give a vapor velocity of 1.5 ft. per second. If the column actually used is 3 ft. 6 in. in diameter and 30 ft. high, calculate the heat loss per hour from the unlagged column, assuming an average surface temperature of 90°C. What per cent is this loss of the total heat to the column?

200. Nitrobenzene is to be steam-distilled at 130°C. at a vacuum of 26 in. of mercury. How many pounds of steam will be needed to distill 2,000 lb. of nitrobenzene?

CHAPTER VI

DRYING

Drying is defined as the removal of water from a paste, slurry, or wet solid to obtain a "commercially dry" solid. As has been noted previously, the term is sometimes used to cover the removal of a small amount of water from liquids (*e.g.*, in the "drying" of an oil) or for the removal from solids of liquids other than water. However, these special cases will not be considered here.

As in the case of evaporation, the two essentials of drying are the supplying of heat (sensible and latent) and the removal of moisture. Where the heat is supplied by contact of the wet charge with hot surfaces, the vapor is generally driven off by boiling, either at atmospheric pressure or under vacuum. On the other hand, where heat is supplied by contact of the wet material with hot gases, the vapor passes into the gas by diffusion through the gas film on the surface of the material.

PRINCIPLES

Fundamental Laws.—The laws of vapor pressure already considered in the study of evaporation and distillation apply to the present subject. Heat-transfer laws are also important to the understanding of the mechanism of drying. In addition to these, it should be noted that *diffusion*, the movement of molecules through a relatively stationary resistance (spaces between particles or a film of gas), is proportional to the difference in pressure at the inlet and outlet boundaries of the resistance. Also, its rate is greater at higher temperatures.

Certain materials, such as textiles, have the property of establishing a definite moisture content, known as "regain" or "equilibrium moisture." If dried bone-dry, they will absorb moisture until again in equilibrium with the atmosphere.

Drying by Hot Surfaces.—When heat is transferred to a material by contact with a hot surface, such as the bottom of a

direct-fired graining kettle, it is obvious that the value of h_c , the convection coefficient, is of controlling importance. Movement of material over the surface and exposure of new, wet material to the surface are therefore desirable. Unless this can be done heat must flow by conduction through the dry solid at very low rates or under large temperature differences in order to effect evaporation of water. Sometimes it is possible to use exceedingly thin layers of material, continually scraping them off as fast as they are dried.

With this method of heat supply, the material tends to remain at the boiling point of the water under the existing pressure as long as a considerable amount of free moisture exists. It then rises in temperature, approaching that of the hot surface. For heat-sensitive materials, therefore, it may be necessary to operate under reduced pressure, so that a relatively low-temperature heating medium can be used to work with very thin layers of material which are dried and removed very quickly.

Drying by Hot Gas.—This method is the one most frequently used. In many cases, hot gases of combustion are brought into direct contact with the wet charge, giving up heat and receiving water thus evaporated during their passage through the drier. In case such contact would be deleterious to the material because of its sensitivity to heat or because contamination of the product would result, air or some other suitable gas may be heated externally and introduced in contact with the charge. In either case (air or combustion gases), the heat given up by the gas in cooling must appear as sensible heat in the charge, latent heat in the increased moisture content of the gas, and in radiation. Radiation may play an important part in transmitting heat to the material if combustion takes place within the drier itself.

For convenience in handling problems involving drying by hot gases, some of the factors most frequently used may be presented in the form of charts. The *humidity* of air, defined as the pounds of water per pound of bone-dry air, is plotted for two ranges of temperature in Figs. 35 and 36, the values of H being multiplied by 100 so that the ordinates represent pounds of water per 100 lb. of bone-dry air for the various temperatures as abscissas. When the moisture content of air at a given temperature is such that the partial pressure of its water vapor corresponds to that of liquid water at the same temperature, the air

is said to be "saturated." By plotting the humidity corresponding to this condition for various temperatures, the "saturation line" can be drawn. For any point on this line, the ordinate represents the pounds of water vapor per 100 lb. of bone-dry air which can be carried at the temperature shown by the abscissa. For any point to the right of this line, the moisture shown by the ordinate at any temperature is not enough to saturate the air, the maximum amount being found by proceeding vertically upward to the saturation line at the same temperature.

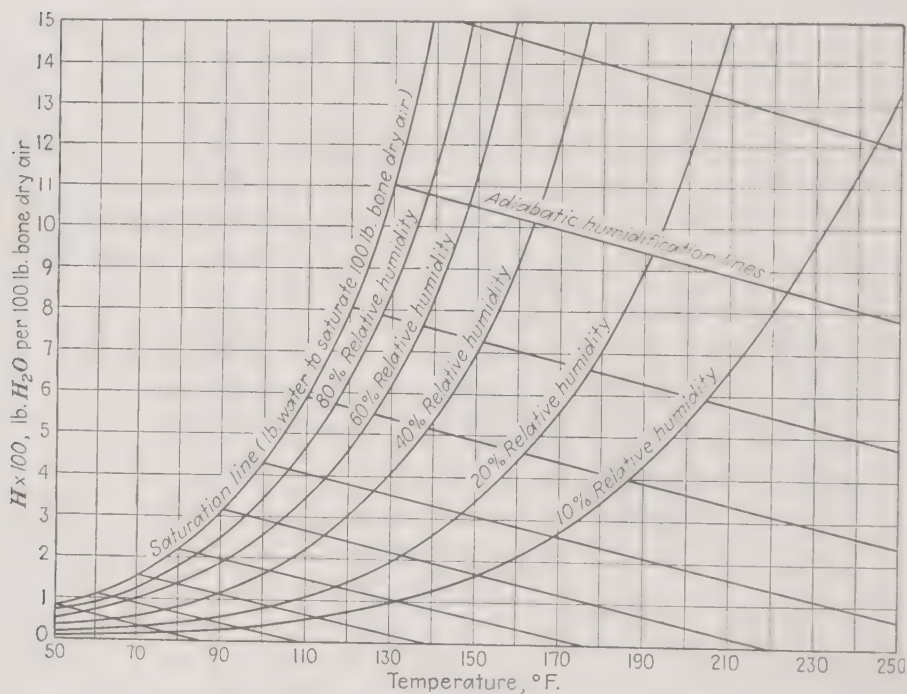


FIG. 35.—Humidity chart, low-temperature range.

Relative humidity is a term frequently used in air-conditioning problems, weather reports, etc. Its value is the ratio of the partial pressure of water vapor in air at any given condition to the partial pressure in saturated air at the same temperature. Thus, if air at 82°F. contains enough water to exert a pressure of 0.55 in. of mercury, it is said to have a relative humidity of 50 per cent because the water in saturated air at 82°F. has a partial pressure of 1.10 in. of mercury. Curves for relative humidity are drawn on the charts, the absolute humidity being found as usual by the ordinate of the given point.

Adiabatic humidification lines, are also shown on Figs. 35 and 36. Each of these represents the change in moisture content of 100 lb. of dry air plus the moisture originally contained in that air under the conditions shown at the extreme right-hand end of the line until it reaches the saturation point while being kept at all times in contact with water and with no heat supply from an outside source or loss of heat by radiation. It can be shown that, in such an adiabatic system, water very quickly reaches an

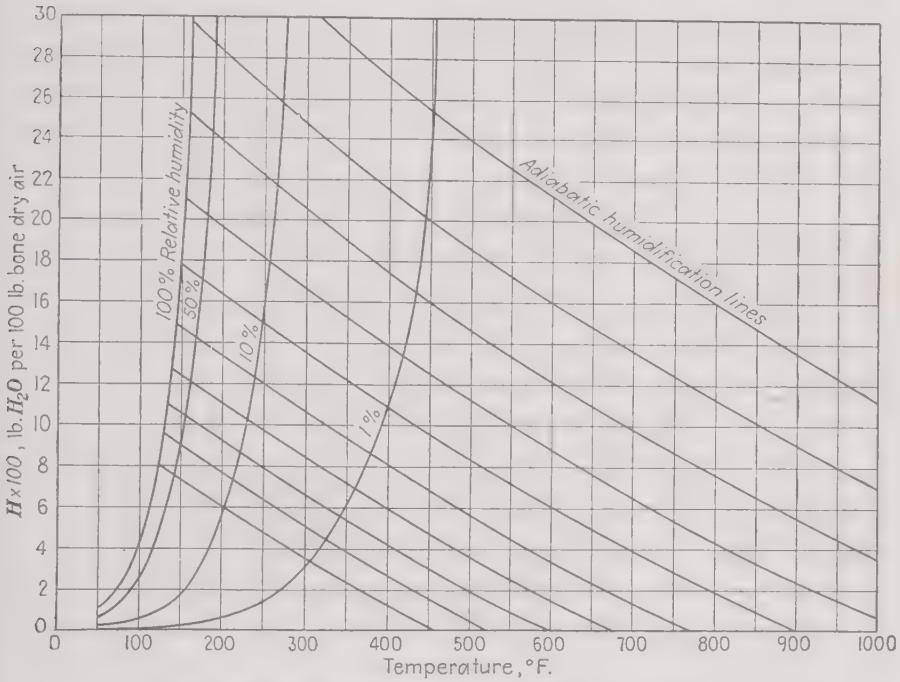


FIG. 36.—Humidity chart, high-temperature range.

equilibrium temperature at which vapor can diffuse into the air as fast as heat can flow into the water to supply latent heat and that this water temperature remains constant until the air finally reaches saturation at this same "wet-bulb temperature." Evidently, then, the wet-bulb temperature of the air is the end point of adiabatic humidification. Since the wet-bulb temperature of air can be determined quite readily by a "psychrometer" and the actual air temperature is obtained by an ordinary dry-bulb thermometer, the absolute humidity of any body of air can be determined by starting from the saturation line at the wet-bulb temperature and moving down to the right on an adiabatic

humidification line to the observed dry-bulb temperature. The number of pounds of water per 100 lb. of bone-dry air is then read from the ordinate of that point.

Figure 37 gives the volume of 1 lb. of bone-dry air at various temperatures and also the volume of 1 lb. of bone-dry air together with the water it carries when saturated at the given temperature. The difference of the ordinates of these curves is the volume of the water vapor itself. Thus, if 1 lb. of air is carrying only 25 per

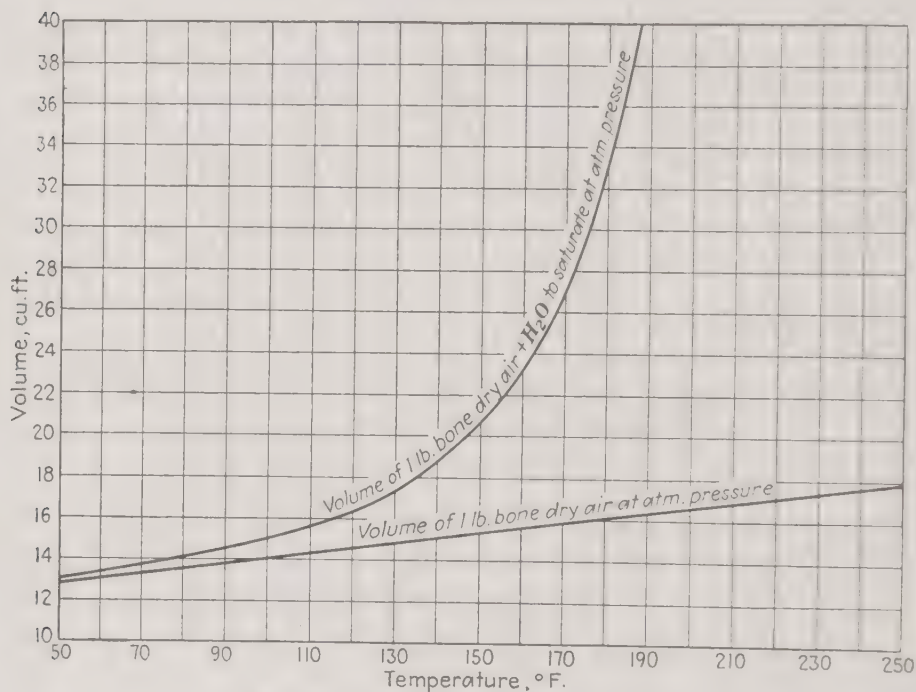


FIG. 37.—Volume-temperature chart.

cent as much water vapor as it could contain at any given temperature, the volume of that pound of air and its water vapor is found by adding 25 per cent of the difference between the curves to the volume of the dry air itself at that temperature.

Figure 38 presents the sensible heat per pound of dry air and also the sensible heat per pound of superheated water vapor, both curves being expressed as B.t.u. per pound above 50°F. For any combination of air and water vapor, so long as no condensation occurs, the changes in sensible heat during heating or cooling can be calculated from these curves, multiplying the number of pounds of air by the difference in sensible heat at the two tem-

peratures in question and likewise multiplying the pounds of water by the difference for water vapor at the two temperatures.

Certain characteristic features of air-drying operations can now be indicated, utilizing the information just given. Since water in contact with hot air (or other gases) tends to assume the wet-bulb temperature of the air, it is evident that a charge of wet material in contact with hot air tends to assume the wet-bulb temperature of that air. As long as the surface of the material, therefore, is kept wet by sufficiently rapid diffusion from the interior, the batch will remain at the wet-bulb temperature, even though the air is very hot.

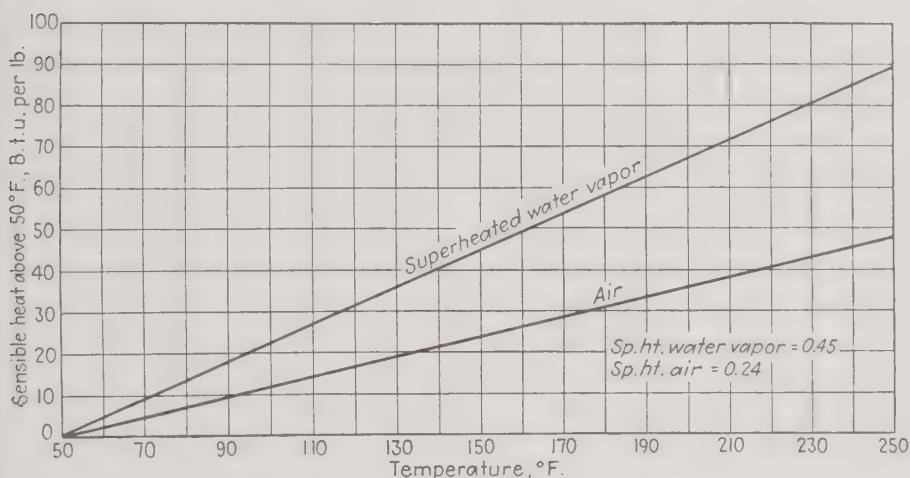


FIG. 38.—Sensible heat-temperature chart.

When the rate of evaporation from the surface exceeds the rate at which water can diffuse from the interior of the cake, the surface becomes dry and its temperature rises. To avoid this, diffusion may be increased and evaporation retarded by using air having a higher wet-bulb temperature, *i.e.*, air of greater humidity at the same temperature. The batch will then tend to assume the new and higher wet-bulb temperature so that diffusion from the interior is increased. At the same time the increase in the humidity of the air means a greater partial pressure of water vapor in the air while that of the liquid surface has increased only a little. The difference in pressure between the liquid surface and the air is thereby decreased and the rate of evaporation is diminished. This deliberate use of increased humidity to maintain a balance between evaporation and

diffusion becomes very important in the drying of soap, lumber, and other materials which "check" or crack if the surface becomes dry while the interior is still wet. Certain materials "caseharden" on the surface if evaporation is too rapid. In some instances live steam has to be fed into a drier to keep the humidity high enough to prevent surface drying during critical stages of the operation.

Most materials dry satisfactorily with air of low humidity. Since the rate of water removal at a given temperature is greater for such materials at higher differences in vapor pressure between batch and air, it is customary to release the air before it becomes highly saturated. This results in poorer heat economy but permits the use of smaller driers for a given daily capacity.

Various formulas have been devised to permit the estimation of the anticipated time required to carry out different types of drying operations. For batch drying at constant temperature, a well-known formula states:

$$\log \frac{W_0}{W} = K\theta$$

W_0 is the initial moisture content of the batch as pounds of water per pound of dry solid; W is the final moisture content; θ is the time in hours; and K is a constant for the particular material, type of drier, temperature, and humidity. For a certain dyestuff, dried in a Proctor shelf drier at 70°C., the value of K was found to be 0.06.

EQUIPMENT

1. Drying by Hot Surfaces. (a) *Pan Driers or "Graining Kettles."*—These are shallow, circular steel or cast-iron pans, usually 18 to 24 in. deep (see Fig. 39). The flat bottoms are scraped by slow-moving (8 to 12 r.p.m.) agitators carried by vertical central shafts which may extend up through suitable castings in the center or may be suspended from an overhead frame. Plant units are usually 6 ft. in diameter, rated at a 300 gal. liquid volume but can be obtained in steel units up to 10 ft. in diameter. Heating is done by direct fire or by jackets on the sides and bottom for steam, Dowtherm, or hot oil. A cover is provided so that vapors can be piped away. Vacuum may be used to permit drying at low temperatures. The product is

discharged by opening a door on the side so that the dried material is then pushed out by the revolving scraper. Steam consumption is about 1.5 lb. per pound of water evaporated. As an example of drying in this machine, Prussian blue was reduced from 63 to 5 per cent moisture in $4\frac{1}{2}$ hr. This machine requires 5 to $7\frac{1}{2}$ hp. for driving the scraper of a 6-ft.-diameter pan.

(b) *Rotary Driers*.—For batch use, these are horizontal cylinders, provided with a door for charging and discharging. The shell is jacketed, the batch being kept in motion by blades on a



FIG. 39.—Vacuum-pan dryer or graining kettle. (Courtesy of Buffalo Foundry & Machine Company.)

revolving shaft. Vacuum may be used on this machine, special attention being given to avoiding leakage at the shaft stuffing boxes, etc. It is also possible to heat this type of drier by an internal cylinder, revolving the body itself. Materials to be dried in a rotary should not be of the type that forms hard cakes on the shell but rather those that break down easily into powder. Steam consumption is about 1.5 lb. per pound of water evaporated. An example is shown in Fig. 40.

For continuous operation, a rotary drier may be heated by direct firing of the shell, feeding wet material at one end and discharging dry product at the other, lifting shelves being provided along the inner wall to lift the material and let it drop

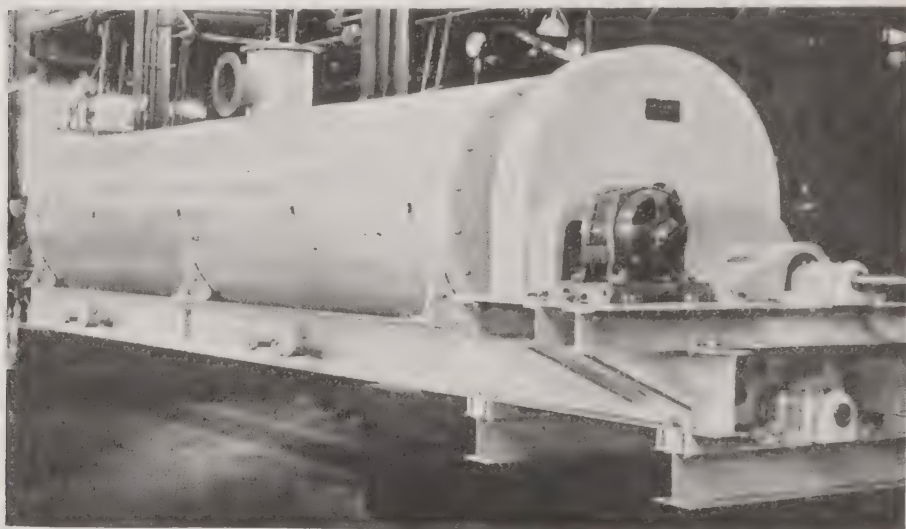


FIG. 40.—Rotary vacuum drier. (Courtesy of F. J. Stokes Machine Company.)

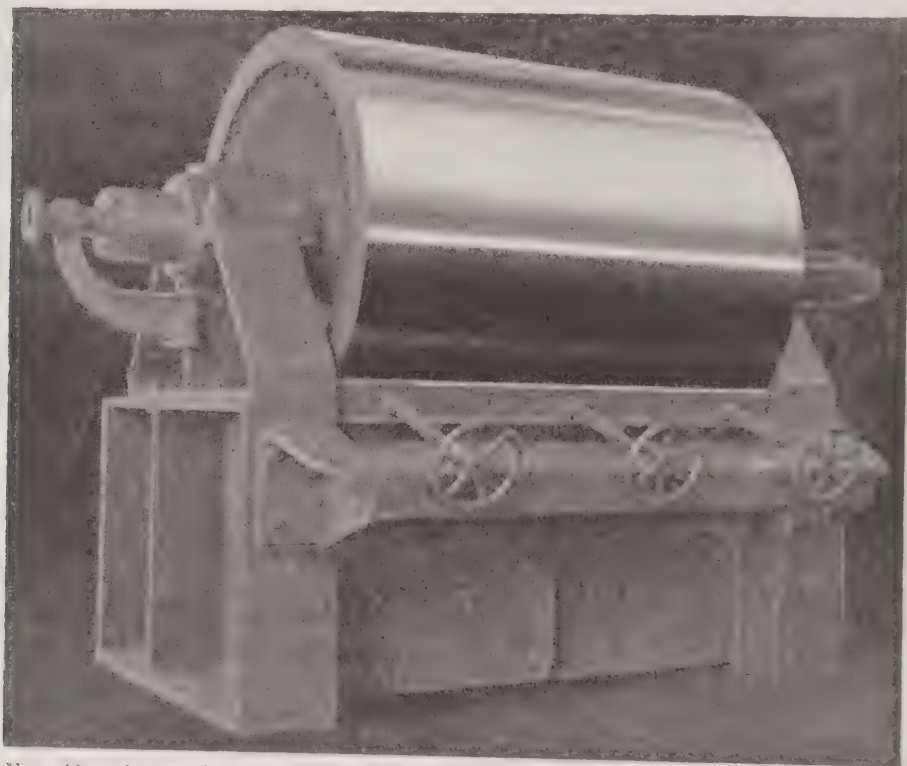


FIG. 41.—Atmospheric-drum drier. (Courtesy of Buffalo Foundry & Machine Company.)

down on a new surface. This method, however, is seldom used, other types being more economical as a rule.

(c) *Drum Driers*.—As the name implies, these are steam-heated drums, revolving on horizontal axes at slow rates of speed, *e.g.*, 1.0 to 5.0 r.p.m. They may be used singly or in pairs, feeding of solution or of wet slurry being done by having the solution sprayed or flowed on or by allowing the drum to dip in a pan of

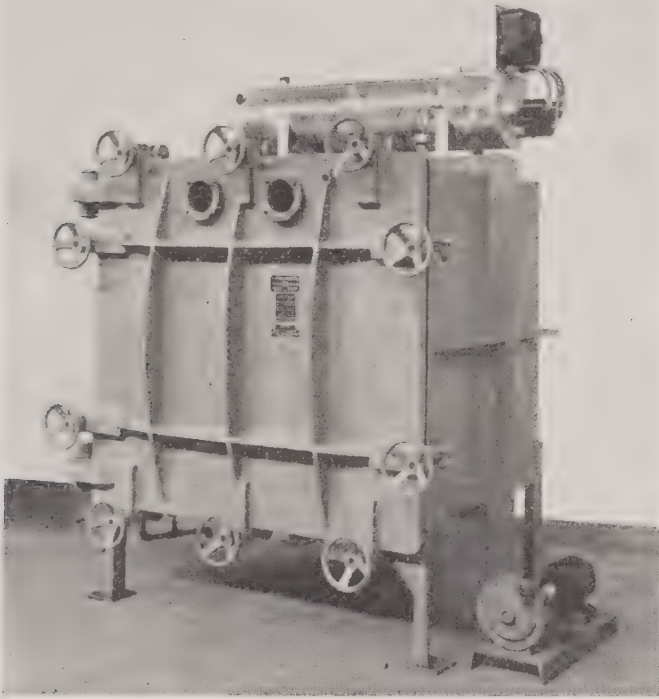


FIG. 42.—Vacuum shelf drier with electrically heated hot-water circulating system. (Courtesy of F. J. Stokes Machine Company.)

charge. As the drum revolves, water is boiled off, leaving a thin film of product which is removed by a sharp *doctor blade*. Single drums may be enclosed in a housing to permit vacuum operation. Capacities vary quite widely with the materials handled and the operating conditions, values from 1 to 10 lb. of dried product per square foot per hour being reported. In general, the higher rates are obtained for the products which still contain 5 to 10 per cent moisture, the lower values being obtained when moisture is reduced to about 1 per cent. Steam consumption is about 1.25 to 2.0 lb. per pound of water evaporated. In general, drum driers are expensive units from the standpoint of

first cost but are often justified by low labor and steam costs and the elimination of grinding. For an example, see Fig. 41.

✓(d) *Shelf Driers*.—Where materials are to be dried by heat from steam or other mediums within shelves, vacuum operation is almost always required. Heat must be transferred from the heating medium through the metal to the surface of the pan containing the charge, then through the metal of the pan, and finally into the material (see Fig. 42). Higher evaporation rates are obtained at higher steam temperatures and at higher vacuums. Ernst and his co-workers at the University of Louisville reported the results of studies on Prussian blue in vacuum driers under several conditions (see *Industrial and Engineering*

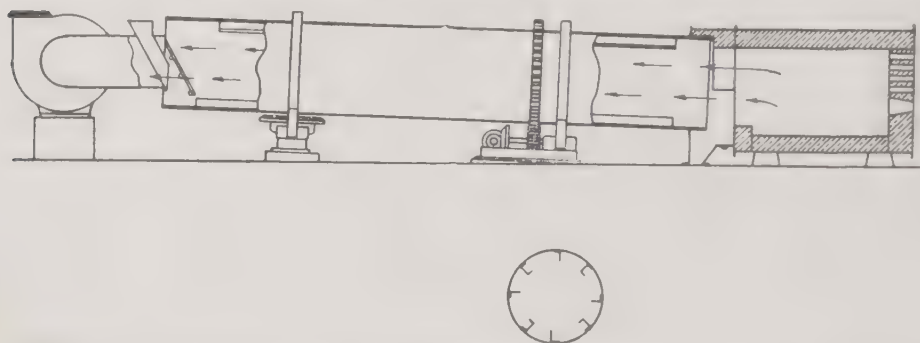


FIG. 43.—Atmospheric rotary drier. Direct counter-current heating. (Courtesy of Hardinge Company.)

Chemistry for October, 1938). Some of their data for the *constant-rate* period are given in Table XXI.

The constant-rate period, which covered about 60 to 70 per cent of the total drying time in their experiments, represents a condition when the free moisture on the surface of the material is kept substantially constant by diffusion from the interior of the cake. When this concentration of surface moisture can no longer be maintained, the *falling-rate period* begins and continues to the end of the operation.

2. Drying by Hot Gas Contact. (a) *Rotary Driers*.—These are generally operated continuously, the feed being carried along by lifting vanes and by the pitch of the drier, which is inclined from the horizontal. As shown by Figs. 43, 44, and 45, various methods of direct, indirect, and semidirect heating may be employed. The hot gases are generally made to flow counter-current to the feed, so that the maximum heat economy is

realized. However, if a material tends to be injured by contact with hot gases after it is dried or if stickiness makes it desirable to produce a rapid surface drying to prevent adherence to the shell, flow may be concurrent. Most ores and many sludges are dried in this type of machine. Thermal efficiencies vary from 30 to 80 per cent according to conditions employed.

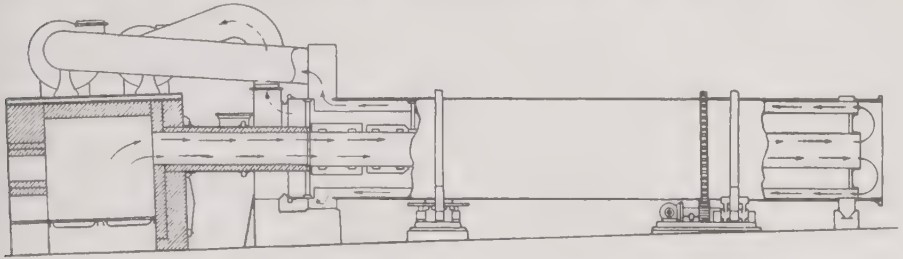


FIG. 44.—Atmospheric rotary drier. Fully indirect heating. (Courtesy of Hardinge Company.)

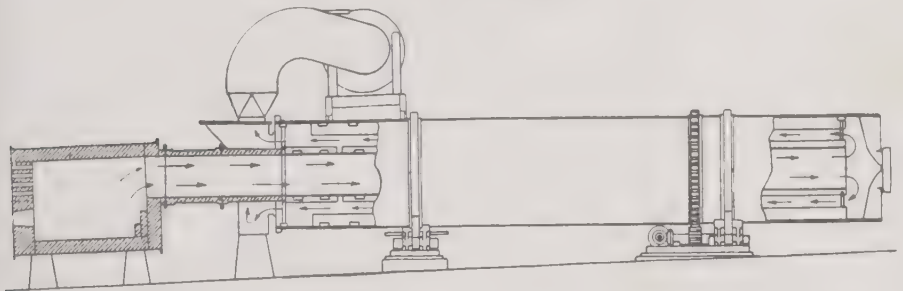


FIG. 45.—Atmospheric rotary drier. Semidirect heating. (Courtesy of Hardinge Company.)

(b) *Spray Driers*.—In this type of equipment the charge is usually a solution, although it may be a thin slurry containing finely divided solids. The heated solution is introduced by a spray nozzle or rapidly whirling disk to project a multitude of “atomized” droplets into a stream of hot gas, frequently the products of combustion from a gas-fired or oil-fired furnace.

Because of high temperature difference as well as great differences in vapor pressure between the liquid and the water vapor in the air, very rapid evaporation takes place. In 15 to 30 sec., the water is evaporated and the resultant dry particles have moved into a lower-temperature zone of the chamber. During the evaporation of most of the water, the solid particle is surrounded by a film of water at a temperature approximately the wet-bulb temperature of the gas so that a very high gas temperature may be used (*e.g.*, 300 to 1200°F.) without injury to delicate materials.

TABLE XXI.—VACUUM DRYING RATES*

Temperature, °C	Vacuum, in.	Lb. of H ₂ O/ sq. ft./hr.
100	18	0.95
	22	1.16
	26	1.10
110	18	1.25
	22	1.35
	26	1.68
120	18	1.45
	22	1.60
	26	1.74
130	18	1.60
	22	1.70
	26	2.44

* Ernst, Ridgway, and Tiller; Practical Vacuum Drying, *Ind. Eng. Chem.*, **30**, 1122-1125 (1938).

Heat requirements are generally in the range of 2000 to 3000 B.t.u. per pound of water evaporated. The products of spray drying are usually found to be small spheres, hollow or spongy, and are ready for packaging without further handling. Investment costs are high on spray driers but their economical operation and the form of the product make them desirable in many large scale operations.

(c) *Shelf Driers*.—Where a number of different materials have to be dried and where the quantity of each does not justify the use of continuous driers, atmospheric shelf driers are widely used. This is especially true in chemical plants where filter cakes of various materials are handled at the rate of a few thousand pounds of each type per day. The driers for batch operation are

rectangular cabinets with doors along the side through which the charge in shallow pans (1 to 2 in. deep) is introduced. In small units, the pans are placed on shelves or on angle-iron supports built into the cabinet. For larger units, the supports are built into trucks on wheels so that the trucks, when filled, can be pushed into the drier on tracks set into the floor. Sufficient space is allowed between the pans so that air can flow over and under each one. Steam-heating coils are provided, usually at the ends of the unit, and suitable fans are arranged to circulate air

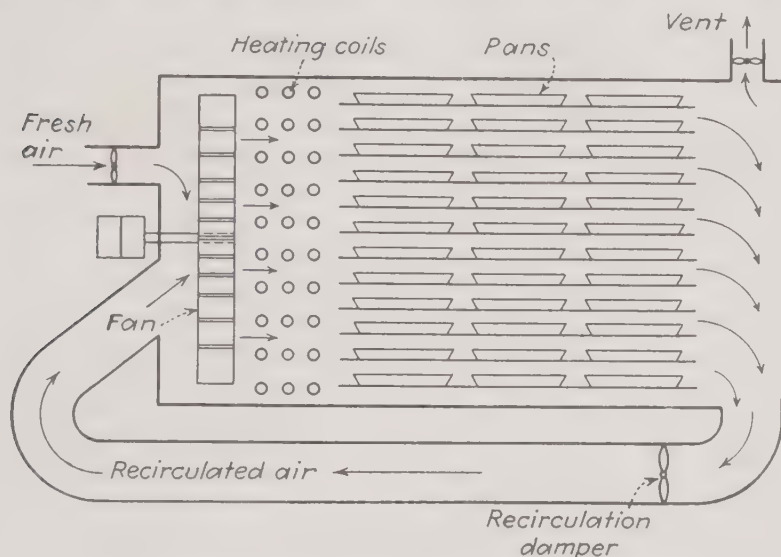


FIG. 46.—Atmospheric shelf drier. Parallel-flow type.

through the space between trays, over the heating coils, and then over the trays again. A controlled amount of fresh air is continuously admitted on the suction side of the fans and an equivalent amount of wet air is discharged on the pressure side.

Two of the most commonly used types of atmospheric shelf driers are shown in Figs. 46 and 47. In the first, the entire mass of air passes through the space between trays "in parallel," then through the heating coils, and then through an external duct to the other side of the cabinet to repeat the cycle. Because of the relatively low velocity of air through all the spaces between trays, power consumption of the fan is low.

In the second design, horizontal baffles are provided so that the air passes through one group of shelves (*e.g.*, six), then is reheated by steam coils, makes a 180-deg. turn as it rises to the next

baffle, passes through another group of the same number of shelves, again makes a 180-deg. turn as it rises through a second heater, etc. The effect is the same as in a multipass condenser, so that much higher linear velocities over the surfaces are obtained than when all of the trays are passed simultaneously. Better heat-transfer values are obtainable with the higher velocity and better air distribution because of higher pressure drops. Since reheating takes place each time after only a small amount of moisture has been picked up per pound of air, the effect is to maintain a relatively constant temperature of the air throughout

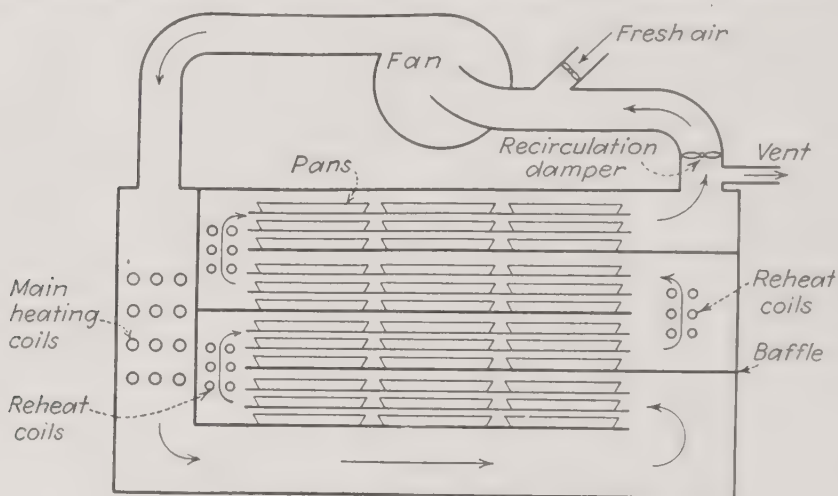


FIG. 47.—Atmospheric shelf drier. Multipass type.

the drier. However, the absolute humidity increases from section to section as the air passes up from the lowest to the highest group of shelves so that the wet-bulb temperature, and therefore the temperature of the batch, is higher in the upper than in the lower pans.

In either of the two types of shelf driers it is important to distribute the air as uniformly as possible over all of the trays; otherwise the whole batch will be held up waiting for certain trays to dry. One common fault is to overload the pans so that the material in certain trays is piled up until it nearly touches the tray above, while in others the wet cake is level with the upper edge of the tray. Such loading interferes very seriously with proper air circulation and results in slow drying rates in those parts of the oven that are blocked off. For best results, all trays should be filled "level full."

In a well-insulated drier of either of the above types, with no openings for air leakage except the proper vent, drying should be carried out with a steam consumption of 2.5 to 3.0 lb. of steam per pound of water evaporated. To accomplish this, care should be taken to reduce the air from the discharge vent as the humidity in the drier decreases. Otherwise, hot air of low humidity is thrown away and the steam consumption can easily increase by 25 per cent or more. Where driers are not kept tight, tests have shown steam consumption as high as 10.0 lb. per pound of water evaporated, due to leakage through cracks and around badly fitting doors.

An interesting study of drying at constant temperature and humidity in shelf driers has been presented by A. E. Stacey in *Industrial and Engineering Chemistry* for December, 1938. He divided materials tested into three classes: (1) those having a very porous structure, such as paper pulp; (2) those of a lumpy or granular nature, such as pigments; and (3) those that case-harden on the surface, such as clays. He then compared the over-all rate of drying for each type of material with the time required to evaporate the same weight of water per square foot from a pan of clear water, using the same difference between the vapor pressure of the water and its partial pressure in the air as he had observed in drying the actual materials. The resultant ratio of time for free water evaporation to the time for complete drying of the product was called the "drying ratio." For the same materials Stacey also calculated the time that would be required if a batch had dried completely at the rate observed during the "constant-rate period," *i.e.*, when there was a completely wetted surface. He divided this calculated time by the actual total over-all time to obtain a "drying criterion." Some of his results are shown in Table XXII.

Following Stacey's work, another study of atmospheric shelf drying was reported by Schaffner and Koehler in the *Transactions of the American Institute of Chemical Engineers* for June, 1939. These authors dried wet sand, $1\frac{1}{2}$ in. deep in 2-in. trays, at temperatures of 150, 170, and 190°F. Like Stacey, they compared their drying rates with those from free water surfaces under the same conditions. They reported the ratio of time for free water evaporation per square foot to evaporation from the sand per square foot during the *constant-rate period* as about 0.9.

It should be observed that Stacey's ratio was based on the *total time* rather than the constant-rate period. One interesting feature of Schaffner and Koehler's work was the determination of the over-all heat-transfer coefficient from air to wet surface during the constant-rate period, assuming that the surface was at the wet-bulb temperature of the air. Some of their data are given in Table XXIII.

Continuous pan driers are used occasionally where the volume of production is great but the material cannot be handled in bulk.

TABLE XXII.—AIR DRYING RATES*

Class	Material	Temperature, °C.	Drying ratio, %	Drying criterion, %
I	Paper pulp, $\frac{1}{4}$ in.	71.1	33.2	68.5
	1 in.	71.1	29.0	48.2
	$\frac{1}{4}$ in.	115.6	32.2	51.0
	1 in.	115.6	31.6	52.1
II	Lithol red, 1 in.	60	106.5	54.0
	Carbon pigment, $\frac{1}{2}$ in.	71.1	60.0	61.4
III	1 in.	71.1	53.0	45.3
	Clay, $\frac{1}{4}$ in.	115.6	27.5	25.0
	1 in.	115.6	18.5	20.4
	2 in.	115.6	16.8	23.3

* A. E. Stacey, Jr., "Evaporation Rates of Moisture from a Wet Material and from a Free Water Surface," *Ind. Eng. Chem.*, **30**, 1385-1389 (1938).

TABLE XXIII.—HEAT-TRANSFER COEFFICIENTS IN AIR DRYING*

Temperature		Relative humidity, %	h_c
Dry bulb, °F.	Wet bulb, °F.		
150	102	20	10.3
	112	30	10.2
	123	45	10.5
170	116	20	9.4
	128	30	10.2
	140	45	11.7
190	130	20	12.4
	142	30	11.1
	147	45	13.1

* R. M. Schaffner and W. A. Koehler, Determination of the Performance and Operating Costs of a Commercial Dryer, *Trans. Am. Inst. Chem. Engrs.*, **35**, 303-321 (1939).

The pans, automatically loaded at one end of the machine, travel through the drier on conveyor chains and discharge automatically at the other end.

A shelf drier without pans, known as the Buettner drier, has been used to a limited extent in this country. It consists of a vertical cylinder carrying horizontal shelves, each with a discharge opening to the shelf below. The wet charge, fed to the top shelf, is moved around by a slowly moving scraper carried by a central shaft and is discharged through the opening onto the shelf below. Here it is moved around to the opening in that shelf and so passes on from shelf to shelf until discharged at the bottom. Hot air, entering at the bottom, passes upward, counter-current to the charge, fans being provided at each level to ensure recirculation at each stage. Excellent heat economy, small floor space, and high production rates are claimed for this unit.

(d) *Conveyor-type Driers*.—Continuous tunnel driers of various types are available, carrying the charge on screens or by other means adapted to the particular product involved. One interesting type is the Aeroform drier of Proctor and Schwartz, by which a wet cake is partially dried on a grooved drum drier. Small cylinders of material, dried sufficiently to hold their shape, are continually discharged from the drum on a moving screen so that hot air can be circulated around each piece as the conveyor moves forward.

(e) *Kiln Mills*.—The Raymond kiln mill (and similar units now manufactured by other companies) combines drying with grinding. Hot gases from an oil-fired furnace are introduced along with the moist feed to a grinding mill. The drying prevents caking in the mill and gives substantial increases in output. The dried product is carried by the air through a fan into a cyclone separator, where it is settled out. A portion of the air, equivalent to the hot gas continually being introduced at the mill, is vented, and the remainder is re-circulated, to be reheated by the hot combustion gas, and again introduced to the grinding chamber.

ILLUSTRATIVE PROBLEMS

Illustration 1.—Five hundred pounds of dry air per hour is saturated at 120°F. , then heated to 242°F. , passed through an adiabatic drier, and finally discharged at 138°F. Determine:

- (a) Total pounds of water in air before heating, per hour.
- (b) Final pounds of water in air when discharged, per hour.
- (c) Water evaporated from material in the drier per hour.
- (d) Relative humidity of air leaving the drier.
- (e) Dew point of air leaving the drier.
- (f) Percentage of saturation of air leaving the drier.
- (g) Number of cubic feet of air per minute before heating.

(a) The condition of the air before heating is "saturated at 120°F." Refer to Fig. 35. Proceed along the base line (abscissa) to 120°F., then vertically upward to the intersection of the 120° temperature line with the saturation curve. The ordinate of this point shows that 100 lb. of dry air, saturated at this temperature, contains 8 lb. of water vapor. Then, for 500 lb. of air,

$$5 \times 8 = 40 \text{ lb. of water (total) in air before heating}$$

(b) During the heating of the air no moisture is added, so that the absolute humidity (pounds of water per pound of dry air) remains constant. Therefore, follow the constant humidity line, 8 lb. per 100 lb. of air, horizontally to the right until it intersects the vertical line representing the final temperature of 242°F. leaving the heater. The problem states that air in this condition enters an adiabatic drier. This means that no heat is added in the drier and that heat losses to the outside are negligible. Accordingly, the air will give up heat to the wet batch as fast as water can evaporate from the batch. This transfer of heat from sensible heat of the air to latent heat of evaporation in the water vapor causes the air to cool and to rise in humidity as more and more water vaporizes into it. The adiabatic humidification line shows the moisture content (per 100 lb. of dry air) at each point of temperature during this adiabatic cooling process. From the entrance to the drier ($100H = 8.0$ and $t = 242^\circ\text{F.}$), follow the adiabatic humidification line to the discharge temperature of 138° (the vertical line upward from 138°). At this point of intersection, read the moisture content of the air leaving the drier as 10.8 lb. per 100 lb. of dry air. Then, for the 500 lb. used,

$$5 \times 10.8 = 54.0 \text{ lb. of water (total) in discharged air}$$

(c) The total water evaporated from the batch of material in the drier must be the increased amount carried by the dis-

charged air. Then,

$$54.0 - 40.0 = 14.0 \text{ lb. of water evaporated per hr.}$$

(d) The relative humidity of the discharged air could be calculated, as defined in the text, by determining the partial pressure equivalent to 10.8 lb. of water vapor per 100 lb. of air and dividing this result by the partial pressure equivalent to saturated air at 138°F. However, it is possible to read it directly from the chart as 80 per cent relative humidity.

(e) The dew point of the air is the temperature to which that air would have to be cooled, without change in humidity, until its moisture content is just enough to saturate it. That is, follow the final humidity condition of the discharged air (10.8 lb. of moisture per 100 lb. of air) horizontally to the left until the saturation line is reached. Then read the temperature corresponding to this point. In this case, the dew point is 129.5°F.

(f) The air, as discharged, contains 10.8 lb. of water per 100 lb. of dry air. From the saturation curve, 100 lb. of dry air, saturated at 138°F., would contain 14.5 lb. of water. The air as discharged is therefore

$$\frac{10.8 \times 100}{14.5} = 74.5\% \text{ saturated}$$

Note that this value is not the same as the per cent relative humidity. The latter does not have a fixed weight of air as a basis.

(g) To determine the volume of the air entering the heater, it is observed that the 500 lb. of dry air is at 120°F., saturated with water. On Fig. 37, the intersection of the vertical line representing 120°F. with the curve for "volume of 1 lb. of bone-dry air + water to saturate it" is found to be at an ordinate of 16.4 cu. ft. Since this is the volume of 1 lb. of air plus its saturation moisture, the required volume for 500 lb. of air plus its saturation moisture is

$$500 \times 16.4 = 8,200 \text{ cu. ft. per hr.}$$

Illustration 2.—An atmospheric rotary drier handles 10 tons of a wet crystalline salt per day, reducing the moisture content from 10 to 1 per cent by means of countercurrent flow of hot air,

entering at 225°F. dry-bulb, 110°F. wet-bulb temperature, and leaving at 150°F. dry-bulb. Calculate:

- (a) Humidity of air entering and leaving the drier.
- (b) Number of pounds of water removed from salt per hour.
- (c) Number of tons of product per 24 hr.
- (d) Diameter of drier to give a linear velocity of 1 ft. per second at the inlet.

(a) Since the wet-bulb temperature of the entering air is 110°F., this point is located on Fig. 35 at the intersection of the vertical line for 110°F. with the saturation line, thus marking the condition which the air would reach if cooled adiabatically until saturated. Follow downward to the right, along the adiabatic humidification line, until the dry-bulb temperature of 225° is reached. This intersection of the dry-bulb temperature and the adiabatic humidification line fixes the actual condition of the entering air. The ordinate of this point, read on the left-hand vertical scale by moving horizontally to the left from the observed intersection, is 3.0 lb. of water per 100 lb. of air. The humidity of the entering air therefore is

$$H_1 = 0.03 \text{ lb. water per lb. of bone-dry air}$$

To find the condition of the air leaving the drier, proceed along the adiabatic humidification line from the original condition (225°F. dry bulb, $H = 0.03$) to the point where this humidification line intersects the vertical line for 150°F. dry bulb. The ordinate of this point is 4.9 lb. of water per 100 lb. of air. This makes the humidity of the outgoing air

$$H_2 = 0.049 \text{ lb. of water per lb. of bone-dry air}$$

The *increase* in moisture content of the air passing through the drier could then be calculated as

$$H_2 - H_1 = 0.049 - 0.030 = 0.019 \text{ lb. of water per lb. of dry air}$$

- (b) The moisture content of the 10 tons of wet salt is

$$10 \times 2,000 \times 0.10 = 2,000 \text{ lb. of water in charge}$$

$$\therefore 20,000 - 2,000 = 18,000 \text{ lb. of bone-dry salt content}$$

The final moisture is 1 per cent, so that the bone-dry salt is 99 per cent of the total.

$$\therefore \frac{18,000 \times 0.01}{0.99} = 182 \text{ lb. of water in product}$$

$$2,000 - 182 = 1,818 \text{ lb. (1,820 lb.) of water removed per day}$$

$$\frac{1,820}{24} = 75.8 \text{ lb. of water removed per hr.}$$

(c) The weight of product is found by subtracting the moisture removed from the original weight of wet salt.

$$(10 \times 2,000) - 1,820 = 20,000 - 1,820 = 18,180 \text{ lb. of product}$$

$$\frac{18,180}{2,000} = 9.09 \text{ tons of product per 24 hr.}$$

(d) To determine air velocity, the weight of dry air is calculated by dividing the total moisture absorbed per hour, as found in (b), by the moisture removed by each pound of dry air, calculated at the end of the discussion on (a) as 0.019 lb.

$$\frac{75.8}{0.019} = 3,990 \text{ lb. of dry air used per hr.}$$

Entering the drier at 225°, the humidity was found to be 0.03 lb. of water per pound of air. Since the temperature at this point is beyond the limit of the curve for saturated air (Fig. 37), the volume of the moisture is found by considering it as superheated steam at atmospheric pressure and at 225°. The Steam Tables give the volume of 1 lb. of superheated steam at 220°F. (atmospheric pressure) as 27.2 cu. ft. The volume at 225° is found by Charles's law, multiplying the given volume by the ratio of absolute temperatures.

$$220^{\circ}\text{F.} = 460 + 220 = 680^{\circ}\text{R.,} \quad \text{and}$$

$$225^{\circ}\text{F.} = 460 + 225 = 685^{\circ}\text{R.}$$

$$\therefore \frac{685}{680} \times 27.2 = 27.4 \text{ cu. ft. per lb. at } 225^{\circ}\text{F.}$$

$$3,990 \times 0.03 = 119.7 \text{ lb. (120) of water enter with dry air per hr.}$$

$$120 \times 27.4 = 3,290 \text{ cu. ft. of water vapor enter per hr.}$$

The volume of the dry air itself at 225°, read from the curve of Fig. 37, is 17.2 cu. ft. per pound.

$$3,990 \times 17.2 = 68,600 \text{ cu. ft. of dry air per hr.}$$

The total volume per hour, entering the drier, is the sum of the dry air and its moisture content.

$$68,600 + 3,290$$

= 71,890 cu. ft. (71,900) of moist air enters the drier per hr.

The volume per second, therefore, is

$$\frac{71,900}{3,600} = 20.0 \text{ cu. ft. per sec.}$$

The cross-sectional area of the drier is found by dividing the volume of gas per second by the linear velocity per second.

$$\frac{20.0}{1.0} = 20 \text{ sq. ft., cross-sectional area}$$

$$\therefore 20 = \frac{\pi D^2}{4}$$

$$D = \sqrt{\frac{80.0}{3.14}} = \sqrt{25.5} = 5.05 \text{ ft. diameter required}$$

A 5-ft.-diameter drier would be selected.

Problems

201. Complete the following table, based on moisture analysis of wet materials:

% of Water	Lb. of H ₂ O per 100 Lb. of Dry Solid
1.0	
3.0	
5.0	
10.0	
20.0	
40.0	
50.0	

202. Complete the following table, based on determination of moisture in air at normal barometric pressure, using Fig. 20 for pressure of saturated vapor:

Temperature, °F.	Partial pressure, in. of mercury	Relative humidity, %	Absolute humidity, lb. of H ₂ O per lb. of dry air
60	0.26		
	0.52		
70	0.26		
	0.52		
	0.74		
80	0.26		
	0.74		
	1.03		

203. Complete the following table for moist air, using charts or tables:

Temperature, °F.	Absolute humidity, lb. of H ₂ O per lb. of dry air	Relative humidity, %	Dew point, °F.
75	_____	75	_____
110	0.03	_____	_____
150	_____	_____	100
175	0.10	_____	_____
125	_____	_____	110
500	_____	Omit	150
750	0.15	Omit	_____

204. What is the wet-bulb temperature of air having the following conditions?

Dry bulb, °F.	Absolute humidity, lb. of H ₂ O per lb. of dry air	Dew point, °F.
200	0.02	_____
150	_____	105
800	0.06	_____

205. What is the moisture content of air, having the following conditions?

Dry bulb, °F.	Wet bulb, °F.	Dew point, °F.
900	150	_____
400	130	_____
180	90	_____

206. Calculate the heat evolved when the following cooling takes place, out of contact with any liquid water:

- 100 lb. of dry air + 10 lb. of water vapor, from 250 to 140°F.
- 105 lb. of wet air, $H = 0.05$, from 200 to 110°F.
- 55 lb. of wet air, $H = 0.10$, from 500 to 200°F.
- 100 lb. of dry air, previously saturated at 90°F. and heated to 1000°F. before cooling to 150°F.
- 150 lb. of wet air, wet-bulb temperature 130°F., dry-bulb 400°F., cooled to 130°F.

207. Calculate the heat required to heat air (and moisture) as follows:

- (a) 10 lb. of dry air, saturated at 80°F., heated to 225°F.
- (b) 525 lb. of wet air, $H = 0.05$, from saturation temperature to 1500°F.
- (c) 100 lb. of dry air, 50 per cent relative humidity at 70°F., heated to 250°F.

208. Two thousand pounds of Prussian blue, 63 per cent moisture, is reduced to 5 per cent moisture in 4.5 hr., using steam at 25 lb. per square inch gage pressure in the jacket of an atmospheric-pressure agitated pan drier. If the batch was charged at 70°F. and discharged at 220°F., what was the steam consumption? The specific heat of the dry solid content can be taken at 0.3 and steam for evaporation as 1.5 lb. per pound of water.

209. A 25 per cent solution of a certain soap is fed at 175°F. to a double drum drier, each drum (24 by 24 in.) being heated by steam at 50 lb. per square inch gage pressure. The drums are rotated at 5 r.p.m. In 30 min., 21.0 lb. of product (2.0 per cent moisture) was obtained. What was the capacity of the drier in pounds of water evaporated per square foot per hour and in pounds of product per square foot per hour? If the specific gravity of the product was 1.05, how thick was the flake produced? Estimate the steam consumption per hour. What percentage of this was radiation loss?

210. A vacuum shelf drier, having 100 sq. ft. of pan area, is used to dry a material similar to Prussian blue under 22 in. vacuum with steam at 6 lb. per square inch gage pressure in the heating shelves. The charge, 50 per cent moisture, is 1 in. deep in the trays and weighs 75 lb. per cubic foot. Estimate the drying time required to remove 95 per cent of the moisture, assuming that the average rate during the "falling rate" period is 50 per cent of that during the "constant rate" period.

211. A gluten feed for cattle is produced at the rate of 98,000 lb. of wet press cake (55 per cent moisture) per 24 hr. A steam-tube, rotary drier, to be installed to deliver a dried product containing 11 per cent moisture, is 6 ft. in diameter by 50 ft. long. Its steam requirement (90 lb. per square inch gage pressure) is said to be 100 b.hp. and its electric power, 15 hp. The following costs are given:

Drier and auxiliaries, installed.....	\$9,000.00
Fixed charges (maintenance, depreciation, etc.)	
per yr.....	20 %
Operating cost (labor, supervision, etc.) per day...	\$10.00
Steam cost per 1,000 lb.....	\$0.40
Electric power per kw.-hr.....	\$0.01

Calculate, per ton of dried product, assuming 300 days per year:

- (a) Number of pounds of water evaporated.
- (b) Number of pounds of steam used.
- (c) Cost of product, itemized.

212. The same operation as in Prob. 211 is to be done by a parallel-current waste-heat drier, using flue gas at 550°F. (dew point 100°F.). The gas is to be discharged at 160°F. from the drier, which would be 7 ft. in diameter and 60 ft. long. The cost, installed, is estimated at \$18,500. Power required for drives, fan, etc. will be 70 hp. Calculate as for Prob. 211:

- (a) Cost of product per ton, itemized.
- (b) Number of cubic feet of gas used per hour, assumed as air.
- (c) Maximum gas velocity, in feet per second.
- (d) Moisture absorbed per 100 lb. of bone-dry gas (air).

213. Air enters an adiabatic drier at 1,200 ft. per minute through a 6-ft.-diameter duct at 70°F. and 61° wet-bulb temperature. It is heated to 175°F. before reaching the material to be dried and leaves the drier at 122°F. The material enters at 70°F. with a moisture content of 24 per cent and leaves with a moisture content of 8 per cent. The specific heat of the product is 0.26. Calculate:

- (a) Number of pounds of water removed per pound of bone-dry air.
- (b) Number of cubic feet of air entering and leaving per minute.
- (c) Number of pounds of water evaporated per hour.
- (d) Number of pounds of material entering and leaving per hour.
- (e) B.t.u. consumption of drier per pound of water evaporated.

214. A hematite ore contains 20 per cent of moisture. If drying costs 9 cents per ton of dry ore and the freight rate is 4 cents per 100 lb., what saving is realized per ton of dry ore by drying before shipment?

215. In a test of a Ruggles-Coles drier, the following data are obtained:

Charge—hematite ore, 30 per cent moisture; dried to 2.5 per cent.

Flue gas—flowing countercurrent, enters at 925°F. with a dew point of 77°F. and leaves at 200°F. Analysis: 9 per cent carbon dioxide, 10 per cent oxygen, 0.2 per cent carbon monoxide.

Coal burned—Analysis: 12 per cent ash, 18 per cent volatile combustible, 65 per cent fixed carbon, 5 per cent moisture.

Calculate the number of cubic feet of (wet) flue gas entering per ton of dried ore leaving, and the number of pounds of coal burned per ton of dried ore produced.

CHAPTER VII

FLOW OF FLUIDS

The transportation of fluids, both liquids and gases, is of major importance in practically every department of a chemical plant. As one of the principal unit operations of chemical engineering, the flow of fluids involves the study of the relation between the quantity of fluid handled and the pressure drop required to produce given rates of flow. It also involves methods of measuring rates of flow of liquids and of gases.

Constant Energy.—The basic principle upon which practically all of our study must depend is the constancy of total energy throughout a system (pipe or other conduit) through which a fluid is moving. Thus, if the total energy put into a quantity of water by a pump on the ground floor of a building is equivalent to 1000 B.t.u. per hour, the same energy must exist in some form in the fluid as it passes the second floor and as it reaches a tank on the roof of the building, assuming no loss by radiation en route. Obviously, the energy in relatively quiet water in a tank on the roof of the building is not in the same form as in the high-pressure, moving stream at the pump outlet on the ground floor; however, since energy can neither be created nor destroyed, it must still exist in forms that balance the 1000 B.t.u. per hour input. For convenience, all these energy quantities are expressed as foot-pounds.

Potential.—The driving force that causes a fluid to move from one point to another is the difference in pressure or *head* at the two points, just as the driving force that causes heat to flow through a given body is the difference in temperature between the source of heat and its delivery point. An important difference between the flow of heat through a conductor and the flow of water through a pipe is that the former takes place without "friction" so that the heat input at one end reappears as heat output at the other end; in the latter case, part of the pressure head at the input end of the pipe is used up in overcoming the frictional resistance of the pipe walls to the movement of the

liquid particles, this "lost head" being converted into heat which raises the temperature of the pipe and the water an equivalent amount but cannot be reconverted into foot-pounds of work.

Head.—The total head on a fluid at any point is expressed as the sum of three separate quantities:

(a) *Potential head*, the vertical distance above that level which is taken as zero. Just as in calculating the heat content of boiler feed water, we take the content at 32°F. as zero, so in calculating potential head, we may take the lowest point in our piping layout as zero. Thus, 1 lb. of water at a point 10 ft. above the lowest level in the system is said to have a potential head of 10 ft. and the energy content of the pound of water at that height is 10 ft.-lb., so that if the water flowed down through a frictionless pipe it would return the 10 ft.-lb. of energy as work for driving a water wheel or other device. Since this potential head for a given point is a fixed distance above the zero line, it is constant, whether the fluid is moving or at rest.

(b) *Pressure head*, or *static head*, the pressure exerted by the fluid against the wall of the containing vessel or pipe at the point under consideration. Thus, at the point mentioned in the previous paragraph, the pound of water in question may be in a pipe extending vertically upward to an open end 20 ft. above that point. The pressure head at that point, therefore, is 20 ft. of water when the pipe is full but no water is flowing. A manometer or pressure gage attached to a nipple on the side of the pipe at the point in question would read 20 ft. of water (or 8.67 lb. per square inch or 17.6 in. of mercury) above atmospheric pressure. Instead of the 20-ft. pipe above the point in question, there may be a closed valve and the pressure may be maintained by a centrifugal pump at the bottom of the system. As long as the pressure gage or manometer still reads 8.67 lb. per square inch, the static head is still equivalent to 20 ft. of water. If the water is flowing, either through the vertical 20-ft. pipe or through a throttling valve, additional pressure will be required to overcome the friction in the line above the point in question. The pressure gage will then read a higher static pressure than when there was no flow, the excess being equivalent to an additional head in feet which is a measure of the friction.

(c) *Velocity head*, the head through which the water would have to fall to acquire the velocity that exists at the point in

question. This head depends only upon the velocity of the fluid, its value in feet of the fluid being

$$H = \frac{V^2}{2g} = \frac{(\text{ft. per sec.})^2}{64.4} \quad (20)$$

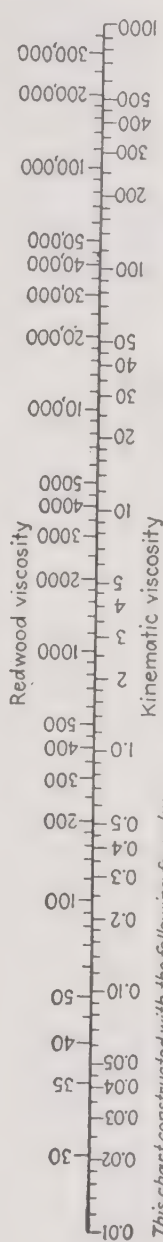
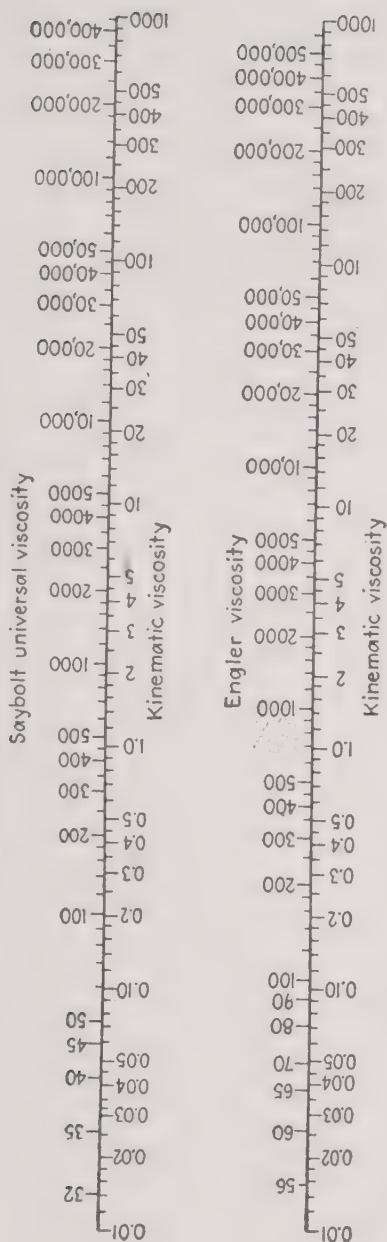
V is the velocity in feet per second and g is the acceleration due to gravity in feet per second per second ($= 32.2$). The pressure gage or manometer on the side of the pipe does not show this velocity head at all. However, if a tube is inserted in the center of the pipe so that its open end is directly opposed to the moving fluid and this tube is then brought to a manometer outside the pipe, a pressure will be read which is the sum of the static and velocity heads. Then, by subtracting from this reading the static pressure shown by the original manometer connected to the side of the pipe, the actual velocity head at the center of the pipe is indicated. The *average* velocity head for the entire cross section of fluid at the point in question varies with the type of flow, the average linear velocity being 0.5 to 0.8 of that at the center of the pipe.

As was previously mentioned, the total head at any point in a fluid system is the sum of the potential, static, and velocity heads, all being expressed as feet of the liquid or gas being handled. Since a head of any fluid has a definite weight, it is often convenient to express head in terms of the *equivalent* pounds per square inch. However, in considering work done, the change in head involved in doing the work must be given in feet. This change in head, multiplied by the pounds of fluid gives foot-pounds of work.

PRESSURE DROP AND RATES OF FLOW

Types of Flow.—At very low velocities for gases and nonviscous liquids and up to fairly high velocities for very viscous liquids, all particles of a fluid seem to move in straight lines. The center of such a body of fluid moves at the maximum velocity; that part in contact with the wall has substantially zero flow, so that the average velocity is 0.5 that at the center. This is called *viscous*, or *streamline*, flow. After passing a certain critical velocity, however, the particles of any fluid cease to move in straight lines but move about in a vigorous mixing motion, thus establishing a condition known as *turbulent* flow. The average velocity of

VISCOSITY CONVERSION CHART



This chart constructed with the following formulas
used by the United States Bureau Standards.

Saybolt universal viscosity: $k = 0.0022 SU - \frac{1.8}{SU}$

Engler viscosity: $k = 0.00147 E - \frac{3.74}{E}$

Redwood viscosity: $k = 0.0026 R - \frac{1.715}{Rw}$

in which:

k = Kinematic viscosity

SU = Saybolt time seconds

E = Engler time seconds

Rw = Redwood time seconds

To convert kinematic viscosity into centipoise units "c" multiply by 100 times the specific gravity of the fluid, or $z = k \times 100 \times \text{specific gravity}$

Converting Baumé degrees into specific gravity by the American Petroleum Institute (API) formula:

$$141.5$$

For fluids lighter than water: $Sp.gr = \frac{141.5}{131.5 + \text{Baumé degrees}}$

$$145$$

For fluids heavier than water: $145 - \text{Baumé degrees}$

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FIG. 48.

the moving fluid is then a greater proportion of the maximum velocity (at the center) than in the case of streamline flow, a ratio of 0.8 being a representative value.

Viscosity.—One property of fluids which is of great importance in problems of fluid flow is viscosity, the resistance to the movement of the molecules on each other. This property may be expressed in various ways, according to the type of instrument (*viscosimeter*) used in determining it or according to the formula in which it is to be used. However, in most cases, it is desirable

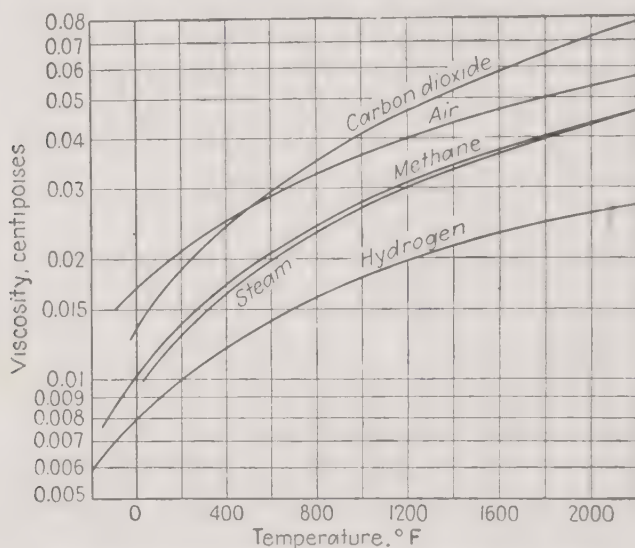


FIG. 49.—Temperature-viscosity curves for gases.

to have the value expressed as “absolute viscosity in centipoises.” Accordingly, when viscosities are given in other terms, such as Saybolt Universal seconds, these must be converted to centipoises. A convenient chart (Fig. 48) permits conversion into kinematic viscosity, k , from which the value in centipoises is given by the relation:

$$\mu = k \times 100 \times \text{sp. gr.}$$

The viscosities of several gases and of several liquids are given in Figs. 49, 50, and 51. It will be observed that the viscosity of a liquid decreases with increasing temperature and that gases become more viscous at higher temperatures. The viscosity of a gas is substantially independent of pressure.

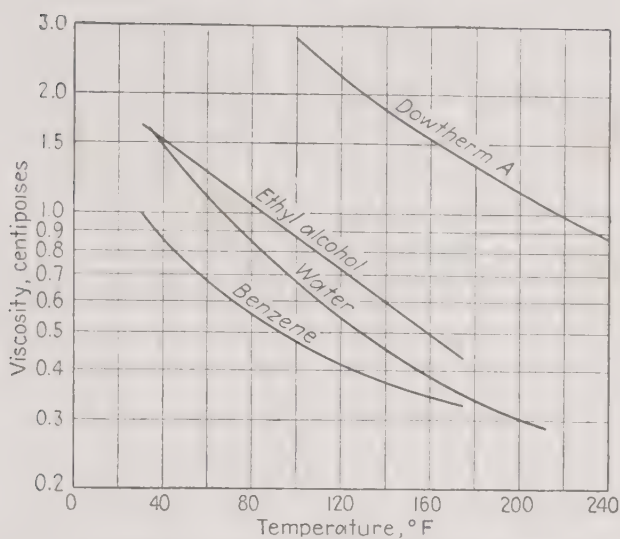


FIG. 50.—Temperature-viscosity curves for low-viscosity liquids.

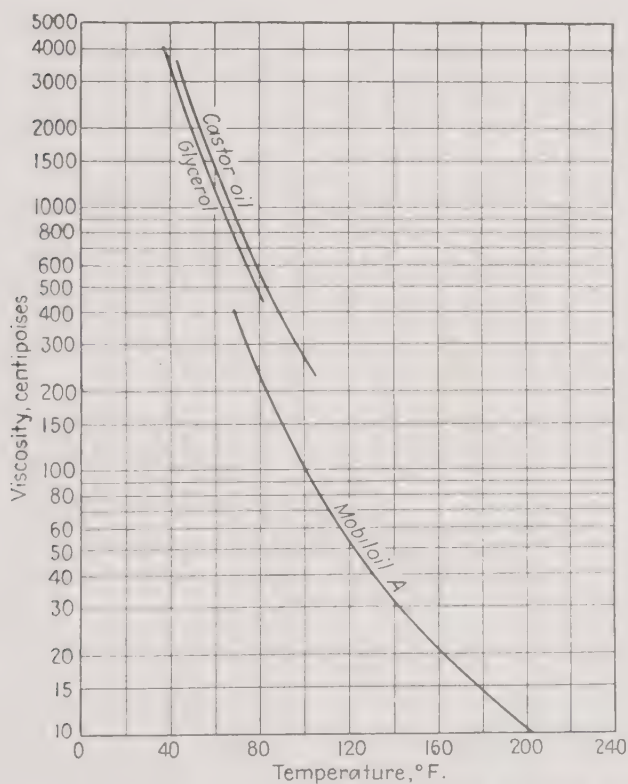


FIG. 51.—Temperature-viscosity curves for high-viscosity liquids.

Calculation.—To determine the energy required to move a given weight of fluid through a system, it is necessary to know the difference in total head between one point and the other, because

$$\text{Energy (ft.-lb.)} = \text{pounds} \times \text{head (ft.)}$$

The difference in total head, as noted above, is

$$\Delta H = (\text{potential}_1 + \text{static}_1 + \text{velocity}_1) - (\text{potential}_2 + \text{static}_2 + \text{velocity}_2) \quad (21)$$

For most cases, the pipe size is not changed throughout the system to be calculated, so that the velocity head is the same at point 2 as at point 1 and will therefore cancel out. Potential head difference is obtained by direct subtraction of the elevations of the two points, leaving change in static head (*i.e.*, pressure) as the item to be calculated. In other words, the problem is to determine the pressure drop caused by friction.

The *Fanning equation* for calculating the pressure drop due to friction in a pipe may be expressed as

$$\Delta p = \frac{fL\rho V^2}{772D} \quad (22)$$

where Δp = pressure drop, in pounds per square inch.

f = friction factor (a variable).

ρ = density of fluid, in pounds per cubic foot. (Greek letter "rho.")

L = *equivalent* length of pipe, in feet.

V = average linear velocity, in feet per second.

D = inside diameter of pipe, in inches.

The friction factor (f) to be used in this equation, depends upon several quantities which are grouped as Reynolds number (Re), whose value is

$$Re = \frac{124 DV\rho}{\mu} \quad (23)$$

The term μ (Greek letter "mu") is the absolute viscosity of the fluid in centipoises at the existing temperature.

By calculating the Reynolds number for a given problem, the friction factor is read from the chart of Fig. 52. It can then be used in the Fanning equation. The sharp break in the curve for friction factor marks the change from streamline to turbulent flow.

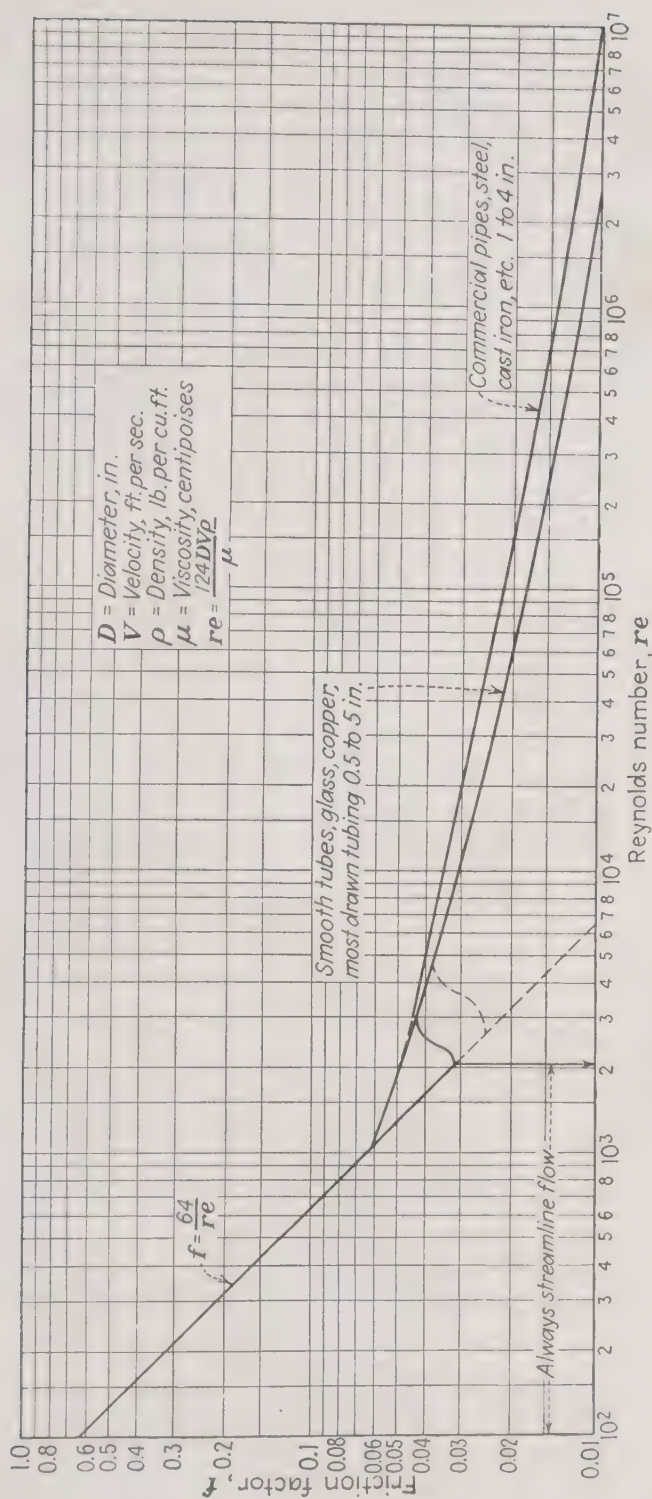


FIG. 52.—Reynolds number-friction factor curves.

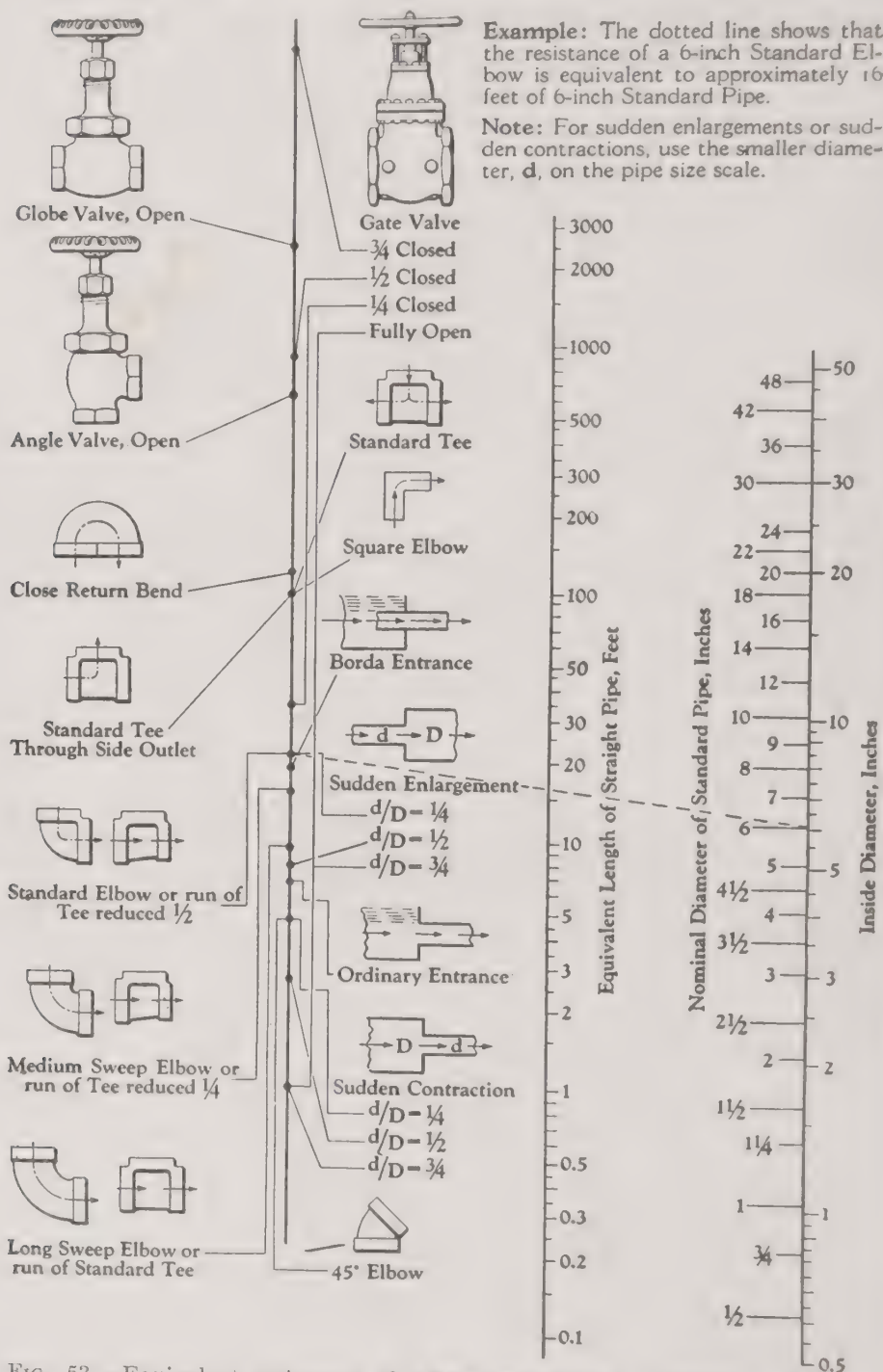


FIG. 53.—Equivalent resistance of valves and fittings. (Courtesy of Crane Company and Foster Wheeler Corporation.)

It is to be noted that the term "equivalent length of pipe in feet" means the actual feet of straight pipe in the line plus the resistance of valves, fittings, and eddy currents at inlet and outlet points. These latter items cause resistance which is expressed in terms of the amount of straight pipe that would cause the same pressure drop. The length of pipe to be added to the actual line length is given by Fig. 53.

FLOW MEASUREMENT BY CONVERSION OF HEADS

Because of the fact that the total energy in a stream of fluid remains constant, except for radiation losses, it is evident that a drop in one variety of head through a certain portion of a system must be balanced by an equivalent increase in another kind of head. This fact is used as a means of measuring rates of flow.

Orifices.—When a fluid passes through a small hole or "orifice" in the line, its linear velocity must increase sufficiently to pass the same number of pounds per second through the small opening as are passing through the larger pipe preceding the orifice. Accordingly, this increase in velocity causes an increase in the velocity head

$$\frac{V^2}{64.4}$$

which must be made up by a decrease in the pressure head. If the static pressure of the fluid is measured at the "upstream" condition, ahead of the orifice, and at a point just below the orifice, where the full effect of the increased velocity is obtained, the difference in head shown by manometers represents the conversion of static to velocity head. Then, if V_1 is velocity upstream and V_2 the velocity through the orifice,

$$V_2^2 - V_1^2 = \text{constant} \times \Delta H \quad (24)$$

There are various factors that influence the calculation of flow through an orifice, including the ratio of the orifice diameter to that of the chamber or line preceding it, the position of the taps leading to the manometers, the Reynolds number of the fluid at orifice conditions, etc. However, by making the orifice diameter not more than 20 per cent of the diameter of the chamber preceding it, taking manometer taps at 0.8 chamber diameter upstream and 0.3 downstream from the orifice, avoiding eddy currents

because of near-by valves and fittings, and making the orifice "sharp-edged in a thin plate," the following formula may be used for many measurements:

$$V = 0.61 \sqrt{64.4H} \quad (25)$$

Here, V is the average velocity through the orifice in feet per second and H is the difference in pressure head shown by the manometers above and below the plate. This value of H must be expressed in *feet of the fluid being measured*. Thus, if some fluid is used in the manometer other than that which is flowing through the orifice, the observed difference in head must be multiplied by the ratio of the specific gravities of measuring fluid to flowing fluid.

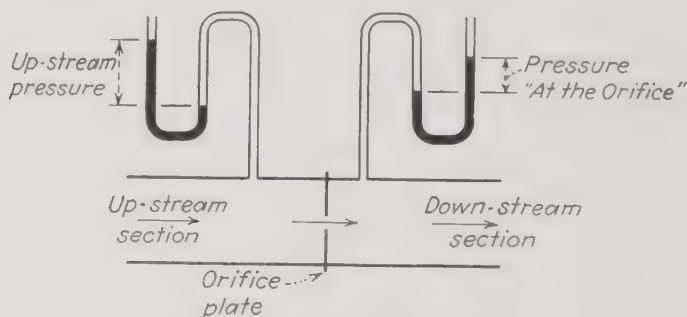


FIG. 54.—Orifice in pipe line.

The orifice is made by drilling a round hole in a $\frac{1}{16}$ - to $\frac{3}{16}$ -in. plate, care being taken to see that the edges of the hole are not rounded or burred. Otherwise, the value of the coefficient of discharge, 0.61 in the above form of the equation, is changed and must be determined by calibrating the orifice against a known rate of flow. An orifice installation is shown diagrammatically in Fig. 54.

The equation, as given, applies to all liquid flows likely to be encountered and to gas flows where the measured pressure drop (H) is not more than 10 per cent of the absolute pressure downstream. For greater pressure drops, gas flows must be calculated by more complicated equations. However, since about 90 per cent of the pressure drop is permanently "lost," *i.e.*, converted into heat, it is advisable to select an orifice that will give a moderate drop, less than 10 per cent of p_2 . This avoids excessive waste of power and simplifies the calculation.

A special case arises for *air at large pressure drops*, when the orifice is not over 20 per cent of the pipe diameter and when the flow is to a chamber where the absolute pressure is less than 53 per cent of the pressure above the orifice. Then, the rate of discharge becomes a fixed amount, regardless of how much p_2 is below $0.53p_1$. For accurate calculation, a coefficient of discharge for the orifice is needed; for a rough approximation, the following formula, *Fliegner's equation*, is convenient:

$$\text{Lb. of air per sec.} = \frac{0.53Ap_1}{\sqrt{T_1}} \quad (26)$$

where A is the area of the orifice in square inches, p_1 is the pressure above the orifice in pounds per square inch, and T_1 is the temperature in degrees Rankine of the air entering the orifice.

A similar condition is found for saturated steam when the downstream pressure is less than 55 per cent of the pressure above the orifice. This is called *Napier's equation*:

$$\text{Lb. of steam per sec.} = \frac{Ap_1}{70} \quad (27)$$

As before, A is the area in square inches and p_1 is the absolute pressure in pounds per square inch of the steam before entering the orifice.

Venturi Meters.—Instead of causing a sudden and violent change in velocity by an orifice, the Venturi meter converts static to pressure head by a gradual decrease in chamber size down to a "throat," followed by a still more gradual change back to the full size of line. With a well-made Venturi meter, the permanent loss in static pressure is only about 10 per cent of the measured drop instead of about 90 per cent with the orifice. The flow may be calculated as

$$\sqrt{V_2^2 - V_1^2} = 0.95 \sqrt{64.4H} \quad (28)$$

In this case, the velocity V_2 is the feet per second at the throat and V_1 is that in the approaching pipe line; H is the measured drop in pressure head (feet of fluid) between the pipe preceding the meter and the throat. The throat diameter is usually 25 to 50 per cent of the upstream diameter. This type of meter is illustrated in Fig. 55.

DIFFERENCE OF HEADS

Since the velocity head in a flowing fluid is a direct measure of the flow rate, this property may be used for determining flow, by the use of a Pitot tube, shown in Fig. 56. This is a combination of a tap on the side of a pipe and an impact tube in the center of the pipe, directly opposed to the direction of flow, both connected to a manometer which thus reads the difference between (velocity +

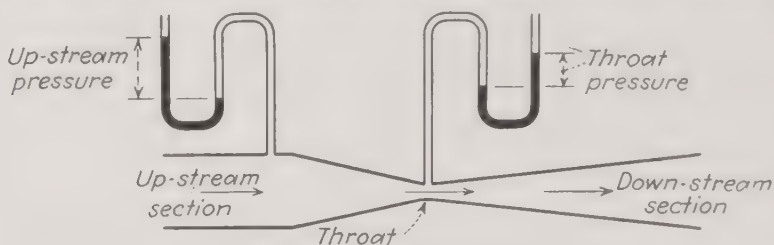


FIG. 55.—Venturi meter.

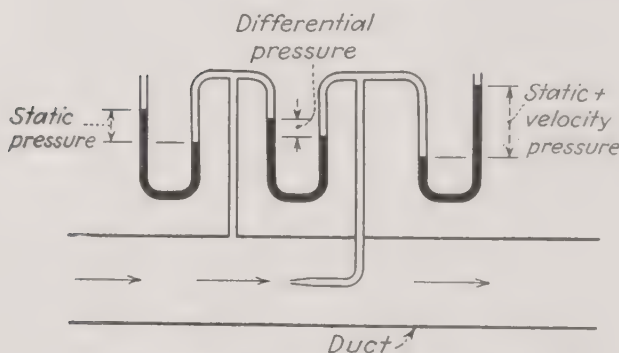


FIG. 56.—Pitot tube in duct.

pressure head) and pressure head only. Then the velocity at the point of the impact tube is

$$u = \sqrt{64.4H} \quad (29)$$

In this case, H is the measured difference, again expressed as feet of fluid flowing.

To get the average over-all velocity (V), this value of u is then multiplied by a suitable factor. For streamline flow, this factor is 0.5. For turbulent flow, at a Reynolds number of 30,000 or more, it is 0.8, intermediate values being obtained for lower Reynolds numbers. In other words, the average velocity for streamline flow is 50 per cent of the maximum velocity; for turbulent flow, it increases to about 80 per cent of the maximum.

OTHER METHODS OF MEASUREMENT

Meters.—Commercial flow meters generally employ the methods already described, the pressure drop through a constriction in the line being translated by suitable mechanical means into the movement of a pointer over a dial or of a marking pen over a chart. By mechanical arrangements, the flow during short intervals of time can be integrated automatically to give total flow in gallons, cubic feet, pounds, etc. for any desired period of time.

One convenient type of instrument that is becoming increasingly popular is the Rotameter. This consists of a tapered glass tube in which a metering float is made to rotate by the friction of the moving fluid against small grooves in the flange around the top of the float. As the quantity of fluid per minute is increased, the float is made to rise higher in the tube, its position relative to marks on the glass tube being a measure of the rate of flow.

PUMPING

The energy input to fluids so that they may be caused to flow is generally supplied by means of pumps. The types commonly used in chemical plants include reciprocating, rotary, and centrifugal pumps for liquids and corresponding compressors, blowers, and fans for gases. It is not possible in this book to cover these in any detail but certain characteristics may be noted.

Reciprocating pumps depend upon positive displacement of a fixed volume of fluid on each stroke. The discharge is therefore the number of strokes per minute times the area of the piston times the length of stroke.

Rotary pumps are also positive displacement devices, delivering a fixed quantity of fluid per revolution. The actual means of displacement may be gears, screws, plungers, or lobes. In any case, the fluid taken in at the suction must be discharged at the exit so that pumping against a closed valve means that something must fail unless a suitable relief valve is provided for by-passing the discharge to the suction. They are suitable for a wide variety of fluids, including everything from gases to viscous liquids, provided that solids are absent. They have high efficiencies and are especially useful for small quantities against relatively high pressures. Because of their close clearances,

rotary pumps are self-priming and can be used for lifting liquids from levels below the pumps.

Centrifugal pumps depend upon increasing the velocity head of fluids by the action of centrifugal force, passing the fluid through an increasing cross-sectional area and thereby re-converting part of the velocity head to pressure head. To secure enough centrifugal force, they operate at much higher speeds than rotaries and have larger diameters. Their efficiencies are generally lower than rotary pumps but they can be operated against a closed valve without danger. Accordingly, centrifugal pumps are used for large quantities of fluids at relatively low pressures and against pressures that vary during operation, *e.g.*, in filling filter presses. Solids can be handled with these pumps. They are not ordinarily self-priming, requiring submerged feeds unless special priming devices are provided.

One feature of centrifugal pumps that is often overlooked is that their discharge capacity and their power consumption normally increase quite sharply with decreasing discharge pressure. Thus, a pump designed for a discharge head of 40 ft. may burn out its motor if allowed to discharge against a 10-ft. head. Care must be taken, therefore, in transferring a centrifugal pump from one service to another to see that it cannot overload its motor in this way. Protection may be afforded by having a small enough line on the discharge to act as a friction brake at high capacities and low heads.

Pump maintenance is of major importance in the operation of many departments. Frequent inspection is necessary to see that glands are adjusted against excessive leakage, that bearings and motors are not running hot, and that lubrication is adequate. It is obvious that packing in glands should not be subjected to excessive pressure by overloading the pumps or by tightening any more than is necessary and that excessive leakage should be checked to see that packing is not worn out.

In some cases, overheated glands may be prevented by keeping a small flow of water over them or even by maintaining an actual flow of water through the stuffing box and around the shaft.

WATER HAMMER

The effect of a sudden closing of a valve in a line carrying liquid is often very serious. Obviously, such a sudden stoppage of

flow requires the conversion of the velocity head into pressure head. Numerically, the effect may be calculated as,

$$H = \frac{c}{g} \Delta V \quad (30)$$

For this equation, H is the increased pressure head in feet, c is the "celerity factor" in feet per second, g is the acceleration of gravity (32.2 ft. per second per second), and ΔV is the change in velocity of the fluid in feet per second. For water in a rigid pipe, $c = 4,720$ ft. per second. Thus, if water, moving at a speed of 1 ft. per second through a pipe, is suddenly brought to rest, the effect is suddenly to add a head of 146 ft. If the velocity is 2 ft. per second, the water hammer effect is 292 ft.

CONTINUOUS SEPARATORS

Mixed fluids must often be separated continuously, *e.g.*, hydrocarbons and water flowing from the condenser of a steam

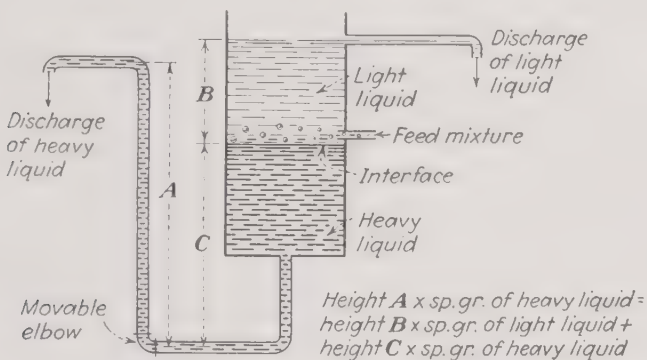


FIG. 57.—Continuous separator for two liquids of different densities.

distillation unit. It is then desired to allow the mixed fluids to enter a chamber of such a size as to permit time enough for the lighter liquid to rise and the heavier liquid to sink below the "interface" where a mixture of both liquids exists, feed being arranged to enter as near the interface as possible. Heavier liquid is piped from the bottom of the chamber through a loop and back to a point outside of the chamber where it flows off as fast as the same type of liquid enters the chamber, while light liquid flows from the top surface of the chamber. The weight of liquid in the external leg, measured from the bottom of that leg to its overflow, must equal the weight of the combination of

liquids from the height of the light liquid overflow to the bottom point of the leg. Figure 57 illustrates such a separator.

ILLUSTRATIVE EXAMPLES

Illustration 1.—Benzene at 20°C. (sp. gr. 0.894) is pumped through 200 ft. of straight 2-in. standard iron pipe with a velocity of 10 ft. per second. The line discharges into a tank 75 ft. above the pump. What is the pressure gage reading at the discharge side of the pump? Neglect inlet and outlet effects.

The pressure indicated by the gage is the head equivalent to the 75 ft. vertical distance plus the pressure required to overcome the friction of the pipe. For the first of these, the pressure due to the 75 ft. of benzene is evidently the weight of a column of benzene 1 sq. in. in cross section and 75 ft. high. Since this material has a specific gravity of 0.894, this column would weigh 0.894 times as much as a column of water of this height. Since it has been shown that 33.9 ft. of water exerts a pressure on 1 sq. in. of 14.7 lb., the weight of a column of water 1 ft. high and 1 sq. in. cross section must be

$$\frac{14.7}{33.9} = 0.434 \text{ lb.}$$

$$\therefore 75 \times 0.894 \times 0.434 = 29.1 \text{ lb. per sq. in. benzene pressure caused by vertical lift}$$

To calculate pressure drop due to friction, the Reynolds number must be determined. From Fig. 50, the viscosity of benzene at 20°C. (= 68°F.) is read as 0.620 centipoises.

The inside diameter of a standard 2-in. pipe, according to Table 5 of the Appendix, is 2.07 in. The density of the benzene is found by multiplying the density of water by the specific gravity of the benzene. These values are combined, using equation (23), to find the Reynolds number.

$$\begin{aligned} \text{Re} &= \frac{124DV\rho}{\mu} \\ &= \frac{124 \times 2.07 \times 10 \times 0.894 \times 62.4}{0.620} \\ &= 231,000 \end{aligned}$$

Using this value of Re, the friction factor for commercial pipe is found from Fig. 52 to be 0.0182. This value of f is then substituted in the Fanning equation, equation (22).

$$\begin{aligned}
 \Delta p &= \frac{fL \rho V^2}{772D} \\
 &= \frac{0.0182 \times 200 \times 0.894 \times 62.4 \times (10)^2}{772 \times 2.07} \\
 &= 12.7 \text{ lb. per sq. in. pressure, to overcome pipe friction}
 \end{aligned}$$

Total pressure head, which would be shown by the gage at the pump discharge, is found by adding the pressure equivalent to the 75 ft. vertical rise to that required for friction drop, the discharge being at zero gage pressure, *i.e.*, atmospheric.

$$29.1 + 12.7 = 41.8 \text{ lb. per sq. in. pressure gage reading}$$

Illustration 2.—Ammonia gas (NH_3) at 150 lb. per square inch absolute pressure and at 260°F . is flowing through a pipe whose inside diameter is 2 in. A sharp-edged orifice, 0.4 in. in diameter, with properly located taps, causes a differential pressure reading of 5 lb. per square inch between the upstream and downstream sides of the orifice. Calculate:

- (a) Velocity through the orifice, in feet per second.
- (b) Pounds of NH_3 flowing per hour.

(a) To apply the orifice equation (25), it is necessary to convert the indicated pressure drop caused by the orifice into the equivalent height of a column of NH_3 gas at the conditions prevailing in the orifice, *i.e.*, at 260°F . and at a pressure of $150 - 5 = 145$ lb. per square inch absolute. The density of the gas in pounds per cubic foot may be calculated from the Law of Perfect Gases, since tables for superheated ammonia are not provided in this book. Pressure must be expressed in pounds per square foot. The value of 145 lb. per square inch is, therefore, multiplied by 144. Temperature must be in degrees Rankine, obtained by adding 460° to the Fahrenheit temperature. The volume is, of course, 1 cu. ft. Then

$$\begin{aligned}
 N &= \frac{pV}{RT} \quad T = 260 + 460 = 720^\circ\text{R.} \\
 &= \frac{145 \times 144 \times 1}{1,543 \times 720} \\
 &= 0.0188 \text{ mol in 1 cu. ft.}
 \end{aligned}$$

$$0.0188 \times 17 = 0.32 \text{ lb. of } \text{NH}_3 \text{ per cu. ft.}$$

If we consider a column of gas 1 sq. ft. in cross section and 1 ft.

high, the weight per square inch on the base of this column is $\frac{1}{144}$ of the weight of the entire cubic foot.

$$\therefore \frac{0.32}{144} = 0.00222 \text{ lb. per sq. in. by a column of gas 1 ft. high}$$

The height of the column to weigh (or exert a pressure of) 5 lb. per square inch is then found by dividing 5 lb. per square inch by the weight of the column of gas 1 sq. in. in cross section and 1 ft. high.

$$H = \frac{5.0}{0.00222} = 2,250 \text{ ft. of NH}_3 \text{ gas at 145 lb. per sq. in. and } 260^\circ\text{F.}$$

Applying equation (25),

$$\begin{aligned} V &= 0.61 \sqrt{64.4 \times 2,250} \\ &= 0.61 \sqrt{145,000} \\ &= 0.61 \times 381 = 232 \text{ ft. per sec. through the orifice} \end{aligned}$$

(b) To determine the pounds of NH_3 flowing, the volume in cubic feet must be calculated. The orifice is 0.4 in. in diameter. The area in square feet is

$$A = \frac{\pi \times (0.4)^2}{4 \times 144} = 0.000872 \text{ sq. ft.}$$

The volume per hour multiplied by the density of the gas in pounds per cubic foot gives the weight.

$$232 \times 0.000872 \times 3,600 \times 0.32 = 233 \text{ lb. of NH}_3 \text{ per hr.}$$

Illustration 3.—Approximately how much steam would flow per hour into a steam distillation unit through a perforated "sparger pipe" containing 20 holes, $\frac{1}{16}$ in. in diameter, steam being at a pressure of 25 lb. per square inch gage and the still being under a 20-in. vacuum?

Since the pressure below the orifices is considerably less than 55 per cent of the pressure above them, Napier's equation (27) may be used for the desired approximation. The steam pressure is approximately 40 lb. per square inch absolute. The area of the holes is

$$A = \frac{20 \times \pi \times (0.0625)^2}{4} = 0.0613 \text{ sq. in.}$$

The flow per second is

$$\begin{aligned} G &= \frac{Ap_1}{70} \\ &= \frac{0.0613 \times 40}{70} = 0.0351 \text{ lb.} \end{aligned}$$

The flow per hour therefore is

$$3,600 \times 0.0351 = 126 \text{ lb. of steam per hr.}$$

Illustration 4.—A Venturi meter with a 2-in. throat is measuring the flow of water in a pipe having an inside diameter of 4 in. The difference in pressure between the throat and the upstream pipe is 6 in. of mercury. Calculate:

- Velocity through the throat, in feet per second.
- Velocity through the pipe, in feet per second.
- Number of gallons of water flowing per minute.

(a) In equation (28), the velocity in the pipe is related to that in the orifice by the inverse ratio of the respective areas, since the quantity flowing per second must be the same at each of these sections. That is, since the volume at each section is the product of linear velocity by cross-sectional area,

$$\begin{aligned} V_1 A_1 &= V_2 A_2 \\ V_1 &= \frac{A_2}{A_1} V_2 \end{aligned}$$

The areas are to each other as the squares of their diameters because

$$\begin{aligned} A_1 &= \frac{\pi D_1^2}{4} \quad \text{and} \quad A_2 = \frac{\pi D_2^2}{4} \\ \therefore V_1 &= \frac{D_2^2}{D_1^2} V_2 \end{aligned}$$

In this case, the throat diameter is 2 in. and the pipe diameter is 4 in. Substituting these values,

$$V_1 = \frac{2^2}{4^2} V_2 = \frac{V_2}{4}$$

The term for differential head, H , must be expressed in feet of fluid flowing. Since mercury has a specific gravity of 13.6,

conversion of 6 in. of mercury to equivalent feet of water gives

$$H = \frac{6 \times 13.6}{12} = 6.80 \text{ ft. of water}$$

The values may now be substituted in equation (28), using $V_2/4$ in place of V_1 so that V_2 is the only unknown.

$$\begin{aligned}\sqrt{V_2^2 - V_1^2} &= 0.95 \sqrt{64.4H} \\ \sqrt{V_2^2 - \left(\frac{V_2}{4}\right)^2} &= 0.95 \sqrt{64.4 \times 6.80}\end{aligned}$$

Squaring both sides of the equation,

$$\frac{15V_2^2}{16} = (0.95)^2 \times 64.4 \times 6.8$$

$$V_2^2 = 422$$

$$V_2 = \sqrt{422} = 20.5 \text{ ft. per sec. velocity at the throat}$$

(b) Since $V_1 = V_2/4$,

$$V_1 = \frac{20.5}{4} = 5.13 \text{ ft. per sec. through 4-in. pipe}$$

(c) The volume in gallons per minute is then found by multiplying the velocity per minute by the cross-sectional area of the pipe in square feet to get cubic feet, and this result by 7.48, the number of gallons in a cubic foot.

$$\text{Area} = \frac{\pi \times (4)^2}{4 \times 144} = 0.0872 \text{ sq. ft.}$$

$$60 \times 5.13 \times 0.0872 \times 7.48 = 201 \text{ gal. per min.}$$

Illustration 5.—A Pitot tube is used to measure a mixture of gases flowing in a 10-in.-diameter duct at 100°F. and atmospheric pressure. The average molecular weight of the mixed gas is said to be 60.0, and its viscosity at 100°F. to be 0.02 centipoises. The difference in pressure between a manometer connected to several taps around the circumference of the duct and a manometer connected to the Pitot tube pointing directly against the direction of gas flow at the center of the duct is 1 in. of water. Calculate:

(a) Average velocity of gas, in feet per second.

(b) Number of pounds of gas flowing per hour.

(a) To apply the Pitot tube formula, it is necessary to convert the differential pressure (1 in. of water) into the equivalent number of feet of gas. This requires a calculation of the gas density. Since the molecular weight is 60, this would be the weight of 359 cu. ft. at standard conditions. Then,

$$60/359 = 0.167 \text{ lb. per cu. ft. (at } 32^{\circ}\text{F. and atmospheric pressure)}$$

At 100°F. , the weight per cubic foot would be less than at 32°F. in the inverse ratio of the absolute temperatures.

$$\therefore 0.167 \times \frac{492}{560} = 0.147 \text{ lb. per cu. ft. at } 100^{\circ}\text{F.}$$

The height of the column of gas equivalent to the column of water used in the manometer will be greater than the height of the water in the inverse ratio of their densities. To obtain the height in feet, the 1 in. of water is divided by 12.

$$\therefore H = \frac{1 \times 62.4}{12 \times 0.147} = 35.4 \text{ ft. of gas}$$

Using equation (29), where u is the maximum velocity, *i.e.*, at the center of the duct where the Pitot tube is placed,

$$\begin{aligned} u &= \sqrt{64.4H} \\ &= \sqrt{64.4 \times 35.4} \\ &= 47.7 \text{ ft. per sec., maximum velocity} \end{aligned}$$

According to the rule stated in the text, the average velocity V will be 50 per cent of the maximum if the flow is streamline and 80 per cent of the maximum if the flow is turbulent and above a Reynolds number of 30,000. Because the maximum velocity is high, assume for the moment that the flow is turbulent and that the average velocity is 80 per cent of the maximum. Then,

$$V = 0.80 \times 47.7 = 38.2 \text{ ft. per sec.}$$

To confirm the assumption of type of flow, calculate the Reynolds number

$$\begin{aligned} \text{Re} &= \frac{124DV\rho}{\mu} \\ &= \frac{124 \times 10 \times 38.2 \times 0.147}{0.02} \\ &= 348,000 \end{aligned}$$

Since this value is far above the 30,000 needed to identify the flow, the assumption was correct. Then,

$$V = 38.2 \text{ ft. per sec., average velocity in duct}$$

(b) The weight of gas flowing per hour is calculated by multiplying cubic feet per hour by density (weight per cubic foot). The area of the 10-in.-diameter duct is found,

$$\text{Area} = \frac{\pi \times (10)^2}{4 \times 144} = 0.545 \text{ sq. ft.}$$

$$\text{Volume} = 38.2 \times 0.545 = 20.8 \text{ cu. ft. per sec.}$$

$$3,600 \times 20.8 \times 0.147 = 11,000 \text{ lb. of gas per hr.}$$

Problems

216. Complete the following table and calculate the Reynolds number of each fluid:

Fluid	Temperature, °F.	Nominal pipe size, in.	Inside diameter, in.	Velocity, ft. per sec.	Density, pound per cu. ft.	Viscosity, centi- poises
(a) Water.....	110	1	_____	1	_____	_____
(b) Water.....	160	2	_____	20	_____	_____
(c) Glycerin....	50	1½	_____	15	79.1	_____
(d) Glycerin....	80	1½	_____	6	78.4	_____
(e) Dowtherm (liquid)....	200	1¼	_____	10	_____	_____
(f) Dowtherm (liquid)....	240	2	_____	10	_____	_____
(g) Air.....	100	1	_____	20	_____	_____
(h) Air.....	200	4	_____	10	_____	_____
(i) Steam.....	300	2	_____	5	_____	_____
(j) Steam.....	400	3	_____	50	_____	_____

217. Calculate the pressure drop in pounds per square inch for (a) and (b) in Prob. 216 for 100 ft. of straight clean steel pipe.

218. Glycerin, as in (c), is pumped through 200 ft. of aluminum pipe, the discharge being 60 ft. above the inlet into an open tank. What is the reading of a pressure gage at the inlet? Neglect the effect of fittings.

219. The temperature of glycerin and the pumping rate are changed as shown by (d), other conditions remaining as in Prob. 218. How much energy (horsepower-hours) does the pump deliver in 20 min.? What size motor is required if the pump has an efficiency of 60 per cent?

220. Dowtherm, as in (e), is pumped through a pipe line 150 ft. long, containing two fully open gate valves, six standard elbows, and four standard tees (run). The discharge opens into the jacket of a kettle at a point 25 ft. above the pump, where the line started. Calculate the over-all pressure drop from pump to kettle jacket.

221. Calculate the pressure drop for Dowtherm, as in (f), through 100 ft. of steel pipe, the discharge being 5 ft. lower than the inlet. Neglect fittings.

222. Air, as in (g), must be delivered at the end of a 500-ft. line with a pressure of 50 lb. per square inch absolute. What pressure must the air compressor develop? The line contains 10 standard elbows, two open gate valves, 10 standard tees (run), and one standard tee through side outlet.

223. Steam, as in (j), passes through a clean steel pipe 1,000 ft. long. What is the loss in pressure?

224. An air line at 40 lb. per square inch gage pressure has a 30-gal. tank for trapping out moisture. When the air temperature is 70°F., a $\frac{1}{4}$ -in.-diameter plug is accidentally taken out. How many cubic feet of free air are lost in the 15 min. before a new plug is obtained?

225. Estimate the number of pounds of steam leaking per 24 hr. through a pinhole $\frac{1}{32}$ in. in diameter, steam pressure being 185 lb. per square inch gage.

226. An orifice measuring the flow of methane gas (CH_4) at 100°F., shows a differential pressure of 6 in. of water, the gas being at 30 lb. per square inch absolute pressure. The orifice is 2 in. in diameter, the pipe being 10 in. in diameter and the taps being properly placed. What is the flow in pounds of gas per hour?

227. Water at 70°F. flows through a 6-in. pipe at a velocity of 10 ft. per second. What will be the differential pressure in inches of mercury across a 1-in. orifice in the line?

228. Air at 150°F. and 10 lb. per square inch gage pressure is to be measured by an orifice of such size that the flow of 100 cu. ft. per minute will give a differential of 10 in. of water on a manometer. What is the size of the orifice and of the chambers on each side of it?

229. A Venturi meter with a 3-in.-diameter throat is placed in a 9-in. I.D. steel pipe carrying water at 70°F. What is rate of flow in gallons per minute if the differential manometer on the Venturi meter reads 2 in. of mercury?

230. What is the differential reading on a Pitot tube inserted in an 8-in. I.D. pipe carrying 1,600 gal. of water per minute, the average velocity being 80 per cent of that at the center of the pipe?

APPENDIX

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TABLE 1.—DRY SATURATED STEAM: TEMPERATURE TABLE*

Temperature, °F. <i>t</i>	Absolute pressure, lb. per sq. in. <i>p</i>	Specific volume (cu. ft. per lb.)				Enthalpy (B.t.u. per lb.)		Entropy		Temperature, °F. <i>t</i>
		Saturated liquid <i>v_f</i>	Evapora- tion <i>v_{fg}</i>	Saturated vapor <i>v_g</i>	Saturated liquid <i>h_f</i>	Evapora- tion <i>h_{fg}</i>	Saturated vapor <i>h_g</i>	Saturated liquid <i>s_f</i>	Evapora- tion <i>s_{fg}</i>	
32	0.08854	0.01602	3306	3306	0.00	1075.8	1075.8	0.0000	2.1877	32
35	0.09995	0.01602	2947	2947	3.02	1074.1	1077.1	0.0061	2.1709	35
40	0.12170	0.01602	2444	2444	8.05	1071.3	1079.3	0.0162	2.1597	40
45	0.14752	0.01602	2036.4	2036.4	13.06	1068.4	1081.5	0.0262	2.1429	45
50	0.17811	0.01603	1703.2	1703.2	18.07	1065.6	1083.7	0.0361	2.1264	50
60	0.2563	0.01604	1206.6	1206.6	28.06	1059.9	1088.0	0.0555	2.0948	60
70	0.3631	0.01606	867.8	867.8	38.04	1054.3	1092.3	0.0745	2.0647	70
80	0.5069	0.01608	633.1	633.1	48.02	1048.6	1096.6	0.0932	2.0360	80
90	0.6982	0.01610	468.0	468.0	57.99	1042.9	1100.9	0.1115	2.0087	90
100	0.9492	0.01613	350.3	350.3	67.97	1037.2	1105.2	0.1295	1.9826	100
110	1.2748	0.01617	265.3	265.3	77.94	1031.6	1109.5	0.1471	1.9577	110
120	1.6924	0.01620	203.25	203.25	87.92	1025.8	1113.7	0.1645	1.9339	120
130	2.2225	0.01625	157.32	157.32	97.90	1020.0	1117.9	0.1816	1.9112	130
140	2.8866	0.01629	122.39	122.39	107.89	1014.1	1122.0	0.1984	1.8894	140
150	3.718	0.01634	97.06	97.06	117.89	1008.2	1126.1	0.2149	1.8685	150
160	4.741	0.01639	77.27	77.27	127.89	1002.3	1130.2	0.2311	1.8485	160
170	5.992	0.01645	62.04	62.04	137.90	996.3	1134.2	0.2472	1.8293	170
180	7.510	0.01651	50.21	50.23	147.92	990.2	1138.1	0.2630	1.8109	180
190	9.339	0.01657	40.94	40.96	157.95	984.1	1142.0	0.2785	1.7932	190
200	11.526	0.01663	33.62	33.64	167.99	977.9	1145.9	0.2938	1.7762	200
210	14.123	0.01670	27.80	27.82	178.05	971.6	1149.7	0.3090	1.7598	210
220	17.696	0.01672	26.78	26.80	180.07	970.3	1150.4	0.3120	1.7446	220
230	21.185	0.01677	23.13	23.15	188.13	965.2	1153.4	0.3239	1.7401	230
240	20.780	0.01684	19.365	19.382	198.23	958.8	1157.0	0.3387	1.7391	240
250	24.969	0.01692	16.306	16.323	208.34	952.2	1160.5	0.3531	1.7369	250
260	29.825	0.01700	13.804	13.821	218.48	945.5	1164.0	0.3675	1.7323	260
270	35.429	0.01709	11.746	11.763	228.64	938.7	1167.3	0.3817	1.7269	270
280	41.858	0.01717	10.061	10.061	238.84	931.8	1170.6	0.3958	1.7201	280
290	49.203	0.01726	8.628	8.645	249.06	924.7	1173.8	0.4096	1.7140	290
300	57.556	0.01735	7.444	7.461	259.31	917.5	1176.8	0.4234	1.7072	300

300	67.013	0.01745	6.449	6.466	269.59	910.1	1179.7	0.4369	1.1980	1.6350	300
310	77.68	0.01755	5.609	5.626	279.92	902.6	1182.5	0.4504	1.1727	1.6231	310
320	89.66	0.01765	4.896	4.914	290.28	894.9	1185.2	0.4637	1.1478	1.6115	320
330	103.06	0.01776	4.307	4.325	300.68	887.0	1187.7	0.4769	1.1233	1.6002	330
340	118.01	0.01787	3.770	3.788	311.13	879.0	1190.1	0.4900	1.0992	1.5891	340
350	134.63	0.01799	3.324	3.342	321.63	870.7	1192.3	0.5029	1.0754	1.5783	350
360	153.04	0.01811	2.939	2.957	332.18	862.2	1194.4	0.5158	1.0519	1.5677	360
370	173.37	0.01823	2.606	2.625	342.79	853.5	1196.3	0.5286	1.0287	1.5573	370
380	195.77	0.01836	2.317	2.335	353.45	844.6	1198.1	0.5413	1.0059	1.5471	380
390	220.37	0.01850	2.0651	2.0836	364.17	835.4	1199.6	0.5539	0.9832	1.5371	390
400	247.31	0.01864	1.8447	1.8633	374.97	826.0	1201.0	0.5664	0.9608	1.5272	400
410	276.75	0.01878	1.6512	1.6700	385.83	816.3	1202.1	0.5788	0.9386	1.5174	410
420	308.83	0.01894	1.4811	1.5000	396.77	806.3	1203.1	0.5912	0.9166	1.5078	420
430	343.72	0.01910	1.3308	1.3499	407.79	796.0	1203.8	0.6035	0.8947	1.4982	430
440	381.59	0.01926	1.1979	1.2171	418.90	785.4	1204.3	0.6158	0.8730	1.4887	440
450	422.6	0.0194	1.0799	1.0993	430.1	774.5	1204.6	0.6280	0.8513	1.4793	450
460	466.9	0.0196	0.9748	0.9944	441.4	763.2	1204.6	0.6402	0.8298	1.4700	460
470	514.7	0.0198	0.8811	0.9009	452.8	751.5	1204.3	0.6523	0.8083	1.4606	470
480	566.1	0.0200	0.7972	0.8172	464.4	739.4	1203.7	0.6645	0.7868	1.4513	480
490	621.4	0.0202	0.7221	0.7423	476.0	726.8	1202.8	0.6766	0.7653	1.4419	490
500	680.8	0.0204	0.6545	0.6749	487.8	713.9	1201.7	0.6887	0.7438	1.4325	500
520	812.4	0.0209	0.5385	0.5594	511.9	686.4	1198.2	0.7130	0.7006	1.4136	520
540	962.5	0.0215	0.4434	0.4649	536.6	656.6	1193.2	0.7374	0.6568	1.3942	540
560	1133.1	0.0221	0.3647	0.3868	562.2	624.2	1186.4	0.7621	0.6121	1.3742	560
580	1325.8	0.0228	0.2989	0.3217	588.9	588.4	1177.3	0.7872	0.5659	1.3532	580
600	1542.9	0.0236	0.2432	0.2668	617.0	548.5	1165.5	0.8131	0.5176	1.3307	600
620	1786.6	0.0247	0.1955	0.2201	646.7	503.6	1150.3	0.8398	0.4664	1.3062	620
640	2059.7	0.0260	0.1538	0.1798	678.6	452.0	1130.5	0.8679	0.4110	1.2789	640
660	2365.4	0.0278	0.1165	0.1442	714.2	390.2	1104.4	0.8987	0.3485	1.2472	660
680	2708.1	0.0305	0.0810	0.1115	757.3	309.9	1067.2	0.9351	0.2719	1.2071	680
700	3093.7	0.0369	0.0392	0.0761	823.3	172.1	995.4	0.9905	0.1484	1.1389	700
705.4	3206.2	0.0503	0	0.0503	902.7	0	902.7	1.0580	0	1.0580	705.4

* Abridged from "Thermodynamic Properties of Steam," by Joseph H. Keenan and Frederick G. Keyes. Copyright, 1937, by Joseph H. Keenan and Frederick G. Keyes. Published by John Wiley & Sons, Inc., New York. Reprinted by permission from "Steam, Air and Gas Power," 3d ed., by Severns and Degler.

TABLE 2.—DRY SATURATED STEAM: PRESSURE TABLE*

Absolute pressure, lb. per sq. in. p	Temperature, °F. t	Specific volume (cu. ft. per lb.)		Enthalpy (B.t.u. per lb.)		Entropy			Internal energy		Absolute pressure, lb. per sq. in. p	
		Saturated liquid v_f	Saturated vapor v_g	Saturated liquid h_f	Evaporation h_{fg}	Saturated vapor h_g	Saturated liquid s_f	Evaporation s_{fg}	Saturated vapor s_g	Saturated liquid u_f	Saturated vapor u_g	
0.491	79.03	0.01608	652.3	47.05	1049.2	1096.3	0.0914	1.9473	2.0387	47.05	1037.0	0.491
0.736	91.72	0.01611	444.9	59.71	1042.0	1101.7	0.1147	1.8894	2.0041	59.71	1041.1	0.736
0.982	101.14	0.01614	339.2	69.10	1036.6	1105.7	0.1316	1.8481	1.9707	69.10	1044.0	0.982
1.227	108.71	0.01616	274.9	76.65	1032.3	1108.9	0.1449	1.8160	1.9609	76.65	1046.4	1.227
1.473	115.06	0.01618	231.6	82.99	1028.6	1111.6	0.1560	1.7896	1.9456	82.99	1048.5	1.473
1.964	125.43	0.01622	176.7	93.34	1022.7	1116.0	0.1738	1.7476	1.9214	93.33	1051.8	1.964
2.455	133.76	0.01626	143.25	101.66	1017.7	1119.4	0.1879	1.7150	1.9028	101.65	1054.3	2.455
5	162.24	0.01640	73.52	130.13	1001.0	1131.1	0.2347	1.6094	1.8441	130.12	1063.1	5
10	193.21	0.01659	38.42	161.17	982.1	1143.3	0.2835	1.5041	1.7876	161.14	1072.2	10
14.696	212.0	0.01672	26.80	180.07	970.3	1150.4	0.3120	1.4446	1.7566	180.02	1077.5	14.696
15	213.03	0.01672	26.29	181.11	969.7	1150.8	0.3135	1.4415	1.7549	181.06	1077.8	15
16	216.32	0.01674	24.75	184.42	967.6	1152.0	0.3184	1.4313	1.7497	184.37	1078.7	16
18	222.41	0.01679	22.17	190.56	963.6	1154.2	0.3275	1.4128	1.7403	190.50	1080.4	18
20	227.96	0.01683	20.089	196.16	960.1	1156.3	0.3356	1.3962	1.7319	196.10	1081.9	20
25	240.07	0.01692	16.303	208.42	952.1	1160.6	0.3533	1.3606	1.7139	208.34	1085.1	25
30	250.33	0.01701	13.746	218.82	945.3	1164.1	0.3680	1.3313	1.6993	218.73	1087.8	30
35	259.28	0.01708	11.898	227.91	939.2	1167.1	0.3807	1.3063	1.6870	227.80	1090.1	35
40	267.25	0.01715	10.498	236.03	933.7	1169.7	0.3919	1.2844	1.6763	235.90	1092.0	40
45	274.44	0.01721	9.401	243.36	928.6	1172.0	0.4019	1.2650	1.6669	243.22	1093.7	45
50	281.01	0.01727	8.515	250.09	924.0	1174.1	0.4110	1.2474	1.6585	249.93	1095.3	50
55*	287.07	0.01732	7.787	256.30	919.6	1175.9	0.4193	1.2316	1.6509	256.12	1096.7	55
60	292.71	0.01738	7.175	262.09	915.5	1177.6	0.4270	1.2168	1.6438	261.90	1097.9	60
65	297.97	0.01743	6.655	267.50	911.6	1179.1	0.4342	1.2032	1.6374	267.29	1099.1	65
70	302.92	0.01748	6.206	272.61	907.9	1180.6	0.4409	1.1906	1.6315	272.38	1100.2	70
75	307.60	0.01753	5.816	277.43	904.5	1181.9	0.4472	1.1787	1.6259	277.19	1101.2	75
80	312.03	0.01757	5.472	282.02	901.1	1183.1	0.4531	1.1676	1.6207	281.76	1102.1	80
85	316.25	0.01761	5.168	286.39	897.8	1184.2	0.4587	1.1571	1.6158	286.11	1102.9	85
90	320.27	0.01766	4.896	290.56	894.7	1185.3	0.4641	1.1471	1.6112	290.27	1103.7	90
100	327.81	0.01774	4.432	298.40	888.8	1187.2	0.4740	1.1286	1.6026	298.08	1105.2	100
110	334.77	0.01782	4.049	305.66	883.2	1188.9	0.4832	1.1117	1.5948	305.30	1106.5	110

120	341.25	0.01789	3.728	312.44	877.9	1190.4	0.4916	1.0962	1.5878	312.03	1107.6	120
130	347.32	0.01796	3.455	318.81	872.9	1191.7	0.4995	1.0817	1.5812	318.38	1108.6	130
140	353.02	0.01802	3.220	324.82	868.2	1193.0	0.5069	1.0682	1.5751	324.35	1109.6	140
150	358.42	0.01809	3.015	330.51	863.6	1194.1	0.5138	1.0536	1.5694	330.01	1110.5	150
160	363.53	0.01815	2.834	335.93	859.2	1195.1	0.5204	1.0436	1.5640	335.39	1111.2	160
170	368.41	0.01822	2.675	341.09	854.9	1196.0	0.5266	1.0324	1.5590	340.52	1111.9	170
180	373.06	0.01827	2.532	346.03	850.8	1196.9	0.5325	1.0217	1.5542	345.42	1112.5	180
190	377.51	0.01833	2.404	350.79	846.8	1197.6	0.5381	1.0116	1.5497	350.15	1113.1	190
200	381.79	0.01839	2.288	355.36	843.0	1198.4	0.5435	1.0018	1.5453	354.68	1113.7	200
250	400.95	0.01865	1.8438	376.00	825.1	1201.1	0.5675	0.9588	1.5263	375.14	1115.8	250
300	417.33	0.01890	1.5433	393.84	809.0	1202.8	0.5879	0.9225	1.5104	392.79	1117.1	300
350	431.72	0.01913	1.3260	409.69	794.2	1203.9	0.6056	0.8910	1.4966	408.45	1118.0	350
400	444.59	0.0193	1.1613	424.0	780.5	1204.5	0.6214	0.8630	1.4844	422.6	1118.5	400
450	456.28	0.0195	1.0320	437.2	767.4	1204.6	0.6356	0.8378	1.4734	435.5	1118.7	450
500	467.01	0.0197	0.9278	449.4	755.0	1204.4	0.6487	0.8147	1.4634	447.6	1118.6	500
550	476.94	0.0199	0.8424	460.8	743.1	1203.9	0.6608	0.7934	1.4542	458.8	1118.2	550
600	486.21	0.0201	0.7698	471.6	731.6	1230.2	0.6720	0.7734	1.4454	469.4	1117.7	600
650	494.90	0.0203	0.7083	481.8	720.5	1202.3	0.6826	0.7543	1.4374	479.4	1117.1	650
700	503.10	0.0205	0.6554	491.5	709.7	1201.2	0.6925	0.7371	1.4296	488.8	1116.3	700
750	510.86	0.0207	0.6092	500.8	699.2	1200.0	0.7019	0.7204	1.4223	598.0	1115.4	750
800	518.23	0.0209	0.5687	509.7	688.9	1198.6	0.7108	0.7045	1.4153	506.6	1114.4	800
850	525.26	0.0210	0.5327	518.3	678.8	1197.1	0.7194	0.6891	1.4085	515.0	1113.3	850
900	531.98	0.0212	0.5006	526.6	668.8	1195.4	0.7275	0.6744	1.4020	523.1	1112.1	900
950	538.43	0.0214	0.4717	534.6	659.1	1193.7	0.7355	0.6602	1.3957	530.9	1110.8	950
1000	544.61	0.0216	0.4456	542.4	649.4	1191.8	0.7430	0.6467	1.3897	538.4	1109.4	1000
1100	556.31	0.0220	0.4001	557.4	630.4	1187.8	0.7575	0.6205	1.3780	552.9	1106.4	1100
1200	567.22	0.0223	0.3619	571.7	611.7	1183.4	0.7711	0.5956	1.3667	566.7	1103.0	1200
1300	577.46	0.0227	0.3293	585.4	593.2	1178.6	0.7840	0.5719	1.3559	580.0	1099.4	1300
1400	587.10	0.0231	0.3012	598.7	574.7	1173.4	0.7963	0.5491	1.3454	592.7	1095.4	1400
1500	596.23	0.0235	0.2765	611.6	556.3	1167.9	0.8082	0.5269	1.3351	605.1	1091.2	1500
2000	635.82	0.0257	0.1878	671.7	463.4	1135.1	0.8619	0.4230	1.2849	662.2	1065.6	2000
2500	668.13	0.0287	0.1307	730.6	360.5	1091.1	0.9126	0.3197	1.2322	717.3	1030.6	2500
3000	695.36	0.0346	0.0858	802.5	217.8	1020.3	0.9731	0.1885	1.1615	783.4	972.7	3000
3206.2	705.40	0.0503	0.0503	902.7	0	902.7	1.0580	0	1.0580	872.9	872.9	3206.2

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TABLE 3.—PROPERTIES OF SUPERHEATED STEAM*

Absolute pressure, lb. per sq. in. (saturated temperature)		Temperature, °F.												
		200	220	300	350	400	450	500	550	600	700	800	900	1000
1 (101.74)	<i>p</i>	392.6	404.5	452.3	482.2	512.0	541.8	571.6	601.4	631.2	690.8	750.4	809.9	869.5
	<i>h</i>	1150.4	1159.5	1195.8	1218.7	1241.7	1264.9	1288.3	1312.0	1335.7	1383.8	1432.8	1482.7	1533.5
	<i>s</i>	2.0512	2.0647	2.1153	2.1444	2.1720	2.1983	2.2233	2.2468	2.2702	2.3137	2.3542	2.3923	2.4283
5 (162.24)	<i>p</i>	78.16	80.59	90.25	96.26	102.26	108.24	114.22	120.19	126.16	138.10	150.03	161.95	173.87
	<i>h</i>	1148.8	1158.1	1195.0	1218.1	1241.0	1264.5	1288.0	1311.7	1335.4	1383.6	1432.7	1482.6	1533.4
	<i>s</i>	1.8718	1.8857	1.9370	1.9664	1.9942	2.0205	2.0456	2.0692	2.0927	2.1361	2.1767	2.2148	2.2509
10 (193.21)	<i>p</i>	38.85	40.09	45.00	48.03	51.04	54.05	57.05	60.04	63.03	69.01	74.98	80.95	86.92
	<i>h</i>	1146.6	1156.2	1193.9	1217.0	1240.6	1264.0	1287.5	1311.3	1335.1	1383.4	1432.5	1482.4	1533.2
	<i>s</i>	1.7927	1.8071	1.8595	1.8892	1.9172	1.9436	1.9689	1.9924	2.0160	2.0596	2.1002	2.1383	2.1744
14.696 (212.00)	<i>p</i>.....	.....	27.15	30.53	32.62	34.68	36.73	38.78	40.82	42.86	46.94	51.00	55.07	59.13
	<i>h</i>.....	.....	1154.4	1192.8	1216.4	1239.9	1263.5	1287.1	1310.9	1334.8	1383.2	1432.3	1482.3	1533.1
	<i>s</i>.....	.....	1.7624	1.8160	1.8460	1.8743	1.9008	1.9261	1.9498	1.9734	2.0170	2.0576	2.0958	2.1319
20 (227.96)	<i>p</i>.....	.....	.....	22.36	23.91	25.43	26.95	28.46	29.97	31.47	34.47	37.46	40.45	43.44
	<i>h</i>.....	.....	.....	1191.6	1215.6	1239.2	1262.9	1286.6	1310.5	1334.4	1383.9	1432.1	1482.1	1533.0
	<i>s</i>.....	.....	.....	1.7808	1.8112	1.8396	1.8664	1.8918	1.9160	1.9392	1.9829	2.0235	2.0618	2.0978
40 (267.25)	<i>p</i>.....	.....	.....	11.040	11.843	12.628	13.401	14.168	14.93	15.688	17.198	18.702	20.20	21.70
	<i>h</i>.....	.....	.....	1186.8	1211.9	1236.5	1260.7	1284.8	1308.9	1333.1	1381.9	1431.3	1481.4	1532.4
	<i>s</i>.....	.....	.....	1.6994	1.7314	1.7608	1.7881	1.8140	1.8384	1.8619	1.9058	1.9467	1.9850	2.0214
60 (292.71)	<i>p</i>.....	.....	.....	7.259	15.635	8.357	8.884	9.403	9.916	10.427	11.441	12.449	13.452	14.454
	<i>h</i>.....	.....	.....	1181.6	1208.2	1233.6	1258.5	1283.5	1307.4	1331.8	1380.9	1430.5	1480.8	1531.9
	<i>s</i>.....	.....	.....	1.6492	1.6830	1.7135	1.7416	1.7678	1.7926	1.8162	1.8605	1.9015	1.9400	1.9762
80 (312.03)	<i>p</i>.....	.....	.....	.....	5.803	6.22	6.624	7.020	7.410	7.797	8.562	9.322	10.077	10.830
	<i>h</i>.....	.....	.....	.....	1204.3	1230.7	1256.1	1281.1	1305.8	1330.5	1379.9	1429.7	1480.1	1531.3
	<i>s</i>.....	.....	.....	.....	1.6475	1.6791	1.7078	1.7346	1.7598	1.7836	1.8281	1.8694	1.9079	1.9442
100 (327.81)	<i>p</i>.....	.....	.....	.....	4.592	4.937	5.268	5.589	5.905	6.218	6.835	7.446	8.052	8.656
	<i>h</i>.....	.....	.....	.....	1200.1	1227.6	1253.7	1279.1	1304.2	1329.1	1378.9	1428.9	1479.5	1530.8
	<i>s</i>.....	.....	.....	.....	1.6188	1.6518	1.6813	1.7085	1.7339	1.7581	1.8029	1.8443	1.8829	1.9193
120 (341.25)	<i>p</i>.....	.....	.....	.....	3.783	4.081	4.363	4.636	4.902	5.165	5.683	6.195	6.702	7.207
	<i>h</i>.....	.....	.....	.....	1195.7	1224.4	1251.3	1277.2	1302.5	1327.7	1377.8	1428.1	1478.8	1530.2
	<i>s</i>.....	.....	.....	.....	1.5944	1.6287	1.6591	1.6869	1.7127	1.7370	1.7822	1.8237	1.8625	1.8990

140 (353.02)	<i>c</i> <i>h</i> 1221.1 <i>s</i> 1.6087	3.468	3.715 1248.7 1.6515	3.954 1275.2 1.6683	4.186 1300.9 1.6945	4.413 1326.4 1.7190	4.861 1376.8 1.7645	5.301 1427.3 1.8063	5.738 1478.2 1.8451	6.172 1529.7 1.8817
160 (363.53)	<i>c</i> <i>h</i> 1217.6 <i>s</i> 1.5908	3.008	3.230 1246.1 1.6230	3.443 1273.1 1.6519	3.648 1299.3 1.6785	3.849 1325.0 1.7033	4.244 1375.5 1.7491	4.631 1426.4 1.7911	5.015 1477.5 1.8301	5.396 1529.1 1.8667
180 (373.06)	<i>c</i> <i>h</i> 1214.0 <i>s</i> 1.5745	2.649	2.852 1248.5 1.6077	3.044 1271.0 1.6373	3.229 1297.6 1.6642	3.411 1323.5 1.6894	3.764 1374.7 1.7355	4.110 1425.6 1.7776	4.452 1476.8 1.8167	4.792 1528.6 1.8534
200 (381.79)	<i>c</i> <i>h</i> 1210.3 <i>s</i> 1.5594	2.361	2.549 1240.7 1.5937	2.726 1268.9 1.6240	2.895 1295.8 1.6513	3.060 1322.1 1.6767	3.380 1373.6 1.7232	3.693 1424.8 1.7655	4.002 1476.2 1.8048	4.309 1528.0 1.8415
220 (389.86)	<i>c</i> <i>h</i> 1206.5 <i>s</i> 1.5453	2.125	2.301 1237.9 1.5808	2.465 1266.7 1.6117	2.261 1294.1 1.6395	2.772 1320.7 1.6652	3.066 1372.6 1.7120	3.352 1424.0 1.7545	3.634 1474.8 1.7939	3.913 1527.5 1.8308
240 (397.37)	<i>c</i> <i>h</i> 1202.5 <i>s</i> 1.5319	1.9276	2.1120 1234.9 1.5686	2.247 1264.5 1.6003	2.393 1292.4 1.6286	2.533 1319.2 1.6546	2.804 1371.5 1.7017	3.068 1422.2 1.7444	3.327 1474.8 1.7839	3.584 1526.9 1.8209
260 (404.42)	<i>c</i> <i>h</i> 1198.8 <i>s</i> 1.5183	..... ..... ..... .....	1.9183 1232.0 1.5573	2.063 1262.3 1.5897	2.199 1290.5 1.6184	2.330 1317.7 1.6447	2.582 1370.4 1.6922	2.827 1422.3 1.7352	3.067 1474.2 1.7748	3.305 1526.3 1.8118
280 (411.05)	<i>c</i> <i>h</i> 1195.0 <i>s</i> 1.5046	..... ..... ..... .....	1.7674 1228.9 1.5464	1.9047 1260.0 1.5796	2.033 1288.7 1.6087	2.156 1316.2 1.6354	2.392 1369.4 1.6834	2.621 1421.5 1.7265	2.845 1473.5 1.7662	3.066 1525.8 1.8033
300 (417.33)	<i>c</i> <i>h</i> 1191.2 <i>s</i> 1.4910	..... ..... ..... .....	1.6364 1225.8 1.5360	1.7675 1257.6 1.5701	1.8891 1286.8 1.5998	2.005 1314.7 1.6268	2.227 1368.3 1.6751	2.442 1420.6 1.7184	2.652 1472.8 1.7582	2.859 1525.2 1.7954
350 (431.72)	<i>c</i> <i>h</i> 1187.4 <i>s</i> 1.4744	..... ..... ..... .....	1.3734 1217.7 1.5119	1.4923 1251.5 1.5481	1.6010 1282.1 1.5792	1.7036 1310.9 1.6070	1.8980 1365.5 1.6563	2.084 1418.5 1.7002	2.266 1471.1 1.7403	2.445 1523.8 1.7777
400 (444.50)	<i>c</i> <i>h</i> 1183.6 <i>s</i> 1.4582		1.1744 1208.8 1.4892	1.2851 1245.1 1.5281	1.3843 1277.2 1.5607	1.4770 1306.9 1.5894	1.6508 1362.7 1.6398	1.8161 1416.4 1.6842	1.9767 1469.4 1.7247	2.134 1522.4 1.7623

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TABLE 3.—PROPERTIES OF SUPERHEATED STEAM.*—(Continued)

Absolute pressure, lb. per sq. in. (saturated temperature)		Temperature, °F.													
		500	550	600	620	640	660	680	700	800	900	1000	1200	1400	1600
450 (456.28)	<i>v</i> ...	1.1231	1.2155	1.3005	1.3332	1.3632	1.3967	1.4278	1.4548	1.6074	1.7516	1.8928	2.170	2.443	2.714
	<i>h</i> ...	1238.4	1272.0	1302.8	1314.6	1326.2	1337.7	1348.8	1359.9	1414.3	1467.7	1521.0	1628.6	1738.7	1851.9
500 (467.01)	<i>s</i> ...	1.5095	1.5437	1.5735	1.5845	1.5951	1.6054	1.6153	1.6250	1.6699	1.7108	1.7486	1.8177	1.8803	1.9381
	<i>v</i> ...	0.9927	1.0800	1.1591	1.1893	1.2188	1.2478	1.2763	1.3044	1.4405	1.5715	1.6996	1.9504	2.197	2.442
550 (476.94)	<i>h</i> ...	1231.3	1266.8	1298.6	1310.7	1322.6	1334.2	1345.7	1357.0	1412.1	1466.0	1519.6	1627.6	1737.9	1851.3
	<i>s</i> ...	1.4919	1.5280	1.5588	1.5701	1.5810	1.5915	1.6016	1.6115	1.6571	1.6982	1.7363	1.8056	1.8683	1.9262
600 (486.21)	<i>v</i> ...	0.8852	0.9686	1.0431	1.0714	1.0989	1.1239	1.1523	1.1783	1.3038	1.4241	1.5414	1.7706	1.9957	2.219
	<i>h</i> ...	1223.7	1261.2	1294.3	1306.8	1318.9	1330.8	1342.5	1354.0	1409.9	1464.3	1518.2	1626.6	1737.1	1850.6
700 (503.16)	<i>s</i> ...	1.4751	1.5131	1.5451	1.5568	1.5680	1.5787	1.5890	1.5991	1.6452	1.6868	1.7250	1.7946	1.8575	1.9155
	<i>v</i> ...	0.7947	0.8753	0.9463	0.9729	0.9988	1.0241	1.0489	1.0732	1.1899	1.3013	1.4096	1.6208	1.8279	2.033
800 (518.23)	<i>h</i> ...	1215.7	1255.5	1289.9	1302.7	1315.2	1327.4	1339.3	1351.1	1407.7	1462.5	1516.7	1625.5	1736.3	1850.0
	<i>s</i> ...	1.4467	1.4863	1.5200	1.5333	1.5443	1.5558	1.5667	1.5773	1.6343	1.6762	1.7147	1.7846	1.8476	1.9056
900 (531.98)	<i>v</i> ...	0.6154	0.7277	0.7934	0.8177	0.8411	0.8639	0.8860	0.9077	1.0108	1.1082	1.2024	1.3853	1.5641	1.7405
	<i>h</i> ...	1209.8	1243.2	1280.6	1294.3	1307.5	1320.3	1332.8	1345.0	1403.2	1459.0	1513.9	1623.5	1734.8	1848.8
1000 (544.61)	<i>s</i> ...	1.4216	1.4653	1.5084	1.5212	1.5333	1.5449	1.5559	1.5665	1.6147	1.6573	1.6963	1.7666	1.8299	1.8881
	<i>v</i> ...	0.5264	0.5873	0.6389	0.6689	0.6924	0.7133	0.7333	0.7533	0.8763	0.9633	1.0470	1.2088	1.3662	1.5214
1100 (556.31)	<i>h</i> ...	1215.0	1260.1	1296.1	1299.4	1305.9	1312.9	1325.9	1338.6	1398.6	1455.4	1511.0	1621.4	1733.2	1847.5
	<i>s</i> ...	1.3961	1.4450	1.4863	1.4938	1.4988	1.5066	1.5187	1.5303	1.5814	1.6257	1.6656	1.7371	1.8009	1.8729
1200 (567.22)	<i>v</i> ...	0.4533	0.5140	0.5673	0.5850	0.5912	0.5912	0.5912	0.5912	0.6878	0.7604	0.8294	0.9615	1.0893	1.2146
	<i>h</i> ...	1198.3	1248.8	1285.9	1289.9	1291.9	1297.0	1303.4	1309.5	1389.2	1448.2	1505.1	1617.3	1730.0	1845.0
1300 (577.94)	<i>s</i> ...	1.3661	1.4150	1.4583	1.4610	1.4610	1.4610	1.4610	1.4610	1.5535	1.6121	1.6525	1.7245	1.7886	1.8474
	<i>v</i> ...	0.4532	0.5132	0.5666	0.5843	0.5905	0.5905	0.5905	0.5905	0.6878	0.7604	0.8294	0.9615	1.0893	1.2146
1400 (587.10)	<i>h</i> ...	1193.0	1243.0	1280.0	1284.0	1286.0	1289.0	1292.0	1295.0	1375.0	1434.0	1491.0	1603.0	1716.0	1831.0
	<i>s</i> ...	1.3639	1.4079	1.4413	1.4413	1.4413	1.4413	1.4413	1.4413	1.5335	1.5995	1.6405	1.7130	1.7775	1.8363
1500 (597.00)	<i>v</i> ...	0.4016	0.4410	0.4738	0.4862	0.4909	0.4909	0.4909	0.4909	0.6191	0.6866	0.7503	0.8716	0.9885	1.1031
	<i>h</i> ...	1188.0	1238.0	1275.0	1279.0	1281.0	1283.0	1285.0	1287.0	1367.0	1426.0	1483.0	1595.0	1708.0	1823.0
1600 (606.00)	<i>s</i> ...	1.4052	1.4413	1.4728	1.4728	1.4728	1.4728	1.4728	1.4728	1.5653	1.6321	1.6833	1.7505	1.8083	1.8663
	<i>v</i> ...	0.3574	0.3912	0.4140	0.4222	0.4222	0.4222	0.4222	0.4222	0.5414	0.6084	0.6703	0.7816	0.8885	1.0011
1700 (614.00)	<i>h</i> ...	1183.0	1233.0	1270.0	1274.0	1276.0	1278.0	1280.0	1282.0	1362.0	1421.0	1478.0	1590.0	1703.0	1818.0
	<i>s</i> ...	1.4016	1.4377	1.4692	1.4692	1.4692	1.4692	1.4692	1.4692	1.5617	1.6285	1.6797	1.7470	1.7997	1.8575
1800 (621.00)	<i>v</i> ...	0.3174	0.3510	0.3738	0.3812	0.3812	0.3812	0.3812	0.3812	0.5004	0.5674	0.6293	0.7406	0.8475	0.9600
	<i>h</i> ...	1178.0	1228.0	1265.0	1269.0	1271.0	1273.0	1275.0	1277.0	1357.0	1416.0	1473.0	1585.0	1698.0	1813.0
1900 (628.00)	<i>s</i> ...	1.3639	1.4079	1.4413	1.4413	1.4413	1.4413	1.4413	1.4413	1.5335	1.5995	1.6405	1.7130	1.7775	1.8363
	<i>v</i> ...	0.2714	0.3050	0.3278	0.3352	0.3352	0.3352	0.3352	0.3352	0.4544	0.5214	0.5833	0.6946	0.8015	0.9140
2000 (635.00)	<i>h</i> ...	1173.0	1223.0	1260.0	1264.0	1266.0	1268.0	1270.0	1272.0	1352.0	1411.0	1468.0	1580.0	1693.0	1808.0
	<i>s</i> ...	1.3639	1.4079	1.4413	1.4413	1.4413	1.4413	1.4413	1.4413	1.5335	1.5995	1.6405	1.7130	1.7775	1.8363

1600 (604.90)	v. h. s.	0.2733 1187.8 1.3489	0.2036 1215.2 1.3741	0.3112 1238.7 1.3952	0.3271 1259.6 1.4137	0.3417 1278.7 1.4303	0.4034 1358.4 1.4964	0.4553 1425.3 1.5476	0.5027 1487.0 1.5914	0.5306 1604.6 1.6669	0.6738 1720.5 1.7328	0.7545 1837.5 1.7926
1800 (621.03)	v. h. s.	..... ..... .....	0.2407 1185.1 1.3377	0.2597 1214.0 1.3638	0.2760 1238.5 1.3855	0.2907 1260.3 1.4044	0.3502 1347.2 1.4765	0.3986 1417.4 1.5301	0.4421 1480.8 1.5752	0.5218 1600.4 1.6520	0.5968 1717.3 1.7185	0.6693 1835.0 1.7786
2300 (635.82)	v. h. s.	..... ..... .....	0.1936 1145.6 1.2045	0.2161 1184.9 1.3300	0.2337 1214.8 1.3564	0.2489 1240.0 1.3783	0.3074 1335.5 1.4576	0.3532 1409.5 1.5139	0.3945 1474.5 1.5603	0.4668 1596.1 1.6384	0.5352 1714.1 1.7055	0.6011 1832.5 1.7660
2500 (668.13)	v. h. s.	..... ..... .....	..... ..... .....	0.1484 1132.3 1.2687	0.1686 1176.8 1.3073	0.1866 1207.3 1.3373	0.2294 1303.6 1.4127	0.2710 1387.8 1.4772	0.3061 1458.4 1.5273	0.3678 1585.3 1.6088	0.4244 1706.1 1.6775	0.4784 1826.2 1.7389
3000 (695.36)	v. h. s.	..... ..... .....	..... ..... .....	..... ..... .....	0.0984 1060.7 1.1966	0.1760 1267.2 1.3690	0.2159 1365.0 1.4439	0.2159 1441.8 1.4984	0.2476 1517.3 1.5484	0.3018 1698.0 1.5837	0.3505 1819.9 1.6540	0.3966 1919.9 1.7163
3206.2 (705.40)	v. h. s.	..... ..... .....	..... ..... .....	..... ..... .....	..... ..... .....	0.1583 1250.5 1.3508	0.1981 1355.2 1.4309	0.2288 1434.7 1.4874	0.2806 1569.8 1.5742	0.2806 1694.6 1.6452	0.3267 1817.2 1.6452	0.3703 1917.2 1.7080
3500	v. h. s.	..... ..... .....	..... ..... .....	..... ..... .....	0.0306 780.5 0.9515	0.1364 1224.9 1.3241	0.1762 1340.7 1.4127	0.2058 1424.5 1.4723	0.2546 1563.3 1.5615	0.2977 1689.8 1.6336	0.3381 1813.6 1.6968	0.3811 1913.6 1.7595
4000	v. h. s.	..... ..... .....	..... ..... .....	..... ..... .....	0.0287 763.8 0.9347	0.1052 1174.8 1.2757	0.1462 1314.4 1.3827	0.1743 1406.8 1.4482	0.2192 1552.1 1.5417	0.2581 1681.7 1.6154	0.2943 1807.2 1.6795	0.3381 1913.6 1.7595
4500	v. h. s.	..... ..... .....	..... ..... .....	..... ..... .....	0.0276 753.5 0.9235	0.0798 1113.9 1.2204	0.1226 1286.5 1.3529	0.1500 1388.4 1.4253	0.1917 1540.8 1.5235	0.2273 1673.5 1.5990	0.2602 1800.9 1.6640	0.2943 1913.6 1.7595
5000	v. h. s.	..... ..... .....	..... ..... .....	..... ..... .....	0.0268 746.4 0.9152	0.0593 1047.1 1.1622	0.1036 1256.5 1.3231	0.1303 1369.5 1.4034	0.1696 1529.5 1.5066	0.2027 1665.3 1.5839	0.2329 1794.5 1.6499	0.2602 1913.6 1.7595
5500	v. h. s.	..... ..... .....	..... ..... .....	..... ..... .....	0.0262 741.3 0.9090	0.0463 985.0 1.1093	0.0880 1224.1 1.2930	0.1143 1349.3 1.3821	0.1516 1518.2 1.4908	0.1825 1657.0 1.5699	0.2106 1788.1 1.6369	0.2329 1913.6 1.7595

* Abridged from "Thermodynamic Properties of Steam," by Joseph H. Keenan and Frederick G. Keyes. Copyright, 1937, by Joseph H. Keenan and Frederick G. Keyes. Published by John Wiley & Sons, Inc., New York. Reprinted by permission from "Steam, Air and Gas Power," 3d ed., by Severns and Degler.

TABLE 4.—PROPERTIES OF DOWTHERM "A"*
(73.5 % diphenyl oxide; 26.5 % diphenyl)

Temperature		Pressure or vacuum		Heat content,† B.t.u. per lb.			Specific heat, liquid	Density, lb. per cu. ft.	
°F.	°C.	Lb. per sq. in. absolute pressure	In. of mercury vacuum	Liquid†	Latent	Total†		Liquid	Vapor
53.6	12.0	.....	.....	0	164	164	0.37		
60	15.6	.....	.....	2.4	163	165	0.38		
70	21.1	.....	.....	6.2	162	168	0.38		
80	26.7	.....	.....	10.1	161	171	0.39		
90	32.2	.....	.....	14.0	160	174	0.39		
100	37.8	.....	.....	18.0	158	176	0.40		
110	43.3	.....	.....	22.0	158	180	0.40		
120	48.9	.....	.....	26.0	157	183	0.40		
130	54.4	.....	.....	30.1	156	186	0.41		
140	60.0	.....	.....	34.2	155	189	0.41		
150	65.6	.....	.....	38.4	154	192	0.42		
160	71.1	.....	.....	42.6	154	197	0.42		
170	76.7	.....	.....	46.9	153.7	201	0.43		
180	82.2	.....	.....	51.2	152.0	203	0.43	63.1	
190	87.8	.....	.....	55.6	151	207	0.44	62.7	
200	93.3	.....	.....	60.0	150	210	0.44	62.5	0.0012
210	98.9	.....	.....	64.5	149	214	0.45	62.3	0.0016
220	104.5	.....	.....	69.0	148	217	0.45	61.9	0.0020
230	110	0.15	29.7	73.6	147	221	0.46	61.6	0.0030
240	115	0.20	29.6	78.2	146	224	0.46	61.4	0.0034
250	121	0.25	29.5	82.9	145	228	0.47	61.1	0.0045
260	127	0.29	29.4	87.7	144	232	0.48	60.8	0.0056
270	132	0.39	29.2	92.6	144	236	0.49	60.5	0.0070
280	137	0.49	29.0	97.5	143	240	0.49	60.1	0.0080
290	143	0.59	28.8	103.0	142	245	0.50	59.9	0.010
300	149	0.74	28.5	108.0	142	250	0.50	59.6	0.012
310	154	0.88	28.2	113.0	141	253	0.51	59.3	0.016
320	160	1.1	27.8	118.0	140	258	0.52	58.9	0.019
330	166	1.3	27.3	123.0	139	262	0.52	58.6	0.022
340	171	1.6	26.8	128.0	138	266	0.53	58.4	0.026
350	177	1.9	26.2	133.0	138	271	0.54	58.1	0.030
360	182	2.2	25.5	138.0	137	275	0.54	57.8	0.036
370	188	2.6	24.7	144.0	136	280	0.55	57.5	0.044
380	193	3.0	23.8	150.0	136	286	0.55	57.3	0.050
390	199	3.5	22.8	156.0	135	291	0.56	57.0	0.060

* Courtesy of Foster Wheeler Corporation.

† Heat is above freezing point, 53.6°F.

TABLE 4.—PROPERTIES OF DOWTHERM "A".*—(Continued)

Temperature		Pressure or vacuum		Heat content,† B.t.u. per lb.			Specific heat, liquid	Density, lb. per cu. ft.	
°F.	°C.	Lb. per sq. in. absolute pressure	In. of mercury vacuum	Liquid†	Latent	Total†		Liquid	Vapor
400	204	4.1	21.7	162.0	134	296	0.57	56.7	0.068
410	210	4.7	20.4	168.0	133	301	0.57	56.5	0.077
420	216	5.4	19.0	174.0	132	306	0.58	56.2	0.090
430	221	6.1	17.5	180.0	131	311	0.59	55.9	0.10
440	227	6.9	16.0	186.0	130	316	0.59	55.7	0.12
450	232	7.8	14.0	192.0	129	321	0.60	55.4	0.14
460	238	8.8	12.0	198.0	128	326	0.60	55.2	0.16
470	243	10	9.0	204.0	127	331	0.61	54.8	0.18
480	249	12	6.0	210.0	125	334	0.62	54.6	0.21
490	254	14	2.0	216.0	124	341	0.62	54.4	0.24
		Lb. per sq. in. gage							
500	258	15	0.0	222.0	123	345	0.63	54.1	0.28
510	266	17	2.0	228.0	121	349	0.63	53.7	0.32
520	271	19	4.0	234.0	120	354	0.64	53.2	0.36
530	277	21	6.0	240.0	119	359	0.64	53.0	0.40
540	282	24	9.0	247.0	118	365	0.65	52.7	0.44
550	288	27	12	253.0	117	370	0.65	52.3	0.48
560	293	30	15	260.0	115	375	0.65	51.9	0.54
570	299	33	18	267.0	114	381	0.66	51.6	0.60
580	304	36	21	274.0	112	386	0.66	51.2	0.67
590	310	39	24	281.0	111	392	0.66	50.8	0.75
600	315	43	28	288.0	110	398	0.66	50.4	0.88
610	321	47	32	295.0	109	404	0.67	50.1	1.00
620	327	51	36	302.0	107	409	0.67	49.8	1.10
630	332	56	41	309.0	106	415	0.67	49.3	1.17
640	338	62	47	316.0	105	421	0.67	49.1	1.24
650	343	68	53	323.0	104	427	0.67	48.6	1.29
660	349	74	59	330.0	102	432	0.68	48.4	1.34
670	354	81	66	337.0	101	438	0.68	47.9	1.40
680	360	88	73	344.0	99	443	0.68	47.5	1.5
690	366	95	80	351.0	98	449	0.68	47.2	1.6
700	371	103	88	358.0	97	455	0.68	46.9	1.7
710	377	111	96	365.0	95	460	0.68	46.3	1.8
720	382	120	105	372.0	93	465	0.68	45.9	1.9
730	388	129	114	379.0	92	471	0.68	45.5	2.1
740	393	139	124	386.0	90	476	0.68	44.9	2.3
750	399	150	135	393.0	89	482	0.68	44.4	2.5

* Courtesy of Foster Wheeler Corporation.

† Heat is above freezing point, 53.6°F.

TABLE 5.—STANDARD DIMENSIONS FOR STANDARD-WEIGHT WROUGHT-IRON,
AND STEEL PIPE

Nominal size, in.	Actual diameter, external, in.	Approximate diameter, internal, in.	Transverse area, internal, sq. in.	Nominal thick- ness, in.	Length of pipe per sq. ft.	
					External surface, ft.	Internal surface, ft.
$\frac{1}{8}$	0.405	0.269	0.057	0.068	9.431	14.199
$\frac{1}{4}$	0.540	0.364	0.104	0.088	7.073	10.493
$\frac{3}{8}$	0.675	0.493	0.191	0.091	5.658	7.747
$\frac{1}{2}$	0.840	0.622	0.304	0.109	4.547	6.141
$\frac{3}{4}$	1.050	0.824	0.533	0.113	3.637	4.635
1	1.315	1.049	0.864	0.133	2.904	3.641
$1\frac{1}{4}$	1.660	1.380	1.495	0.140	2.301	2.767
$1\frac{1}{2}$	1.900	1.610	2.036	0.145	2.010	2.372
2	2.375	2.067	3.355	0.154	1.608	1.847
$2\frac{1}{2}$	2.875	2.469	4.788	0.203	1.328	1.547
3	3.500	3.068	7.393	0.216	1.091	1.245
$3\frac{1}{2}$	4.000	3.548	9.886	0.226	0.954	1.076
4	4.500	4.026	12.730	0.237	0.848	0.948
$4\frac{1}{2}$	5.000	4.506	15.947	0.247	0.763	0.847
5	5.563	5.047	20.006	0.258	0.686	0.756
6	6.625	6.065	28.891	0.280	0.576	0.629
7	7.625	7.023	38.738	0.301	0.500	0.543
8	8.625	8.071	51.161	0.277	0.442	0.473
8	8.625	7.981	50.027	0.322	0.442	0.478
9	9.625	8.941	62.786	0.342	0.396	0.427
10	10.750	10.192	81.585	0.279	0.355	0.374
10	10.750	10.136	80.691	0.307	0.355	0.376
10	10.750	10.020	78.855	0.365	0.355	0.381
11	11.750	11.000	95.033	0.375	0.325	0.347
12	12.750	12.090	114.800	0.330	0.299	0.315
12	12.750	12.000	113.097	0.375	0.299	0.318

Courtesy of The Crane Co.

TABLE 6.—MANTISSAS OF COMMON LOGARITHMS

	0	1	2	3	4	5	6	7	8	9
100	0000	0004	0009	0013	0017	0022	0026	0030	0035	0039
101	0043	0048	0052	0056	0060	0065	0069	0073	0077	0082
102	0086	0090	0095	0099	0103	0107	0111	0116	0120	0124
103	0128	0133	0137	0141	0145	0149	0154	0158	0162	0166
104	0170	0175	0179	0183	0187	0191	0195	0199	0204	0208
105	0212	0216	0220	0224	0228	0233	0237	0241	0245	0249
106	0253	0257	0261	0265	0269	0273	0278	0282	0286	0290
107	0294	0298	0302	0306	0310	0314	0318	0322	0326	0330
108	0334	0338	0342	0346	0350	0354	0358	0362	0366	0370
109	0374	0378	0382	0386	0390	0394	0398	0402	0406	0410
110	0414	0418	0422	0426	0430	0434	0438	0441	0445	0449
11	0414	0453	0492	0531	0569	0607	0645	0682	0719	0755
12	0792	0828	0864	0899	0934	0969	1004	1038	1072	1106
13	1139	1173	1206	1239	1271	1303	1335	1367	1399	1430
14	1461	1492	1523	1553	1584	1614	1644	1673	1703	1732
15	1761	1790	1818	1847	1875	1903	1931	1959	1987	2014
16	2041	2068	2095	2122	2148	2175	2201	2227	2253	2279
17	2304	2330	2355	2380	2405	2430	2455	2480	2504	2529
18	2553	2577	2601	2625	2648	2672	2695	2718	2742	2765
19	2788	2810	2833	2856	2878	2900	2923	2945	2967	2989
20	3010	3032	3054	3075	3096	3118	3139	3160	3181	3201
21	3222	3243	3263	3284	3304	3324	3345	3365	3385	3404
22	3424	3444	3464	3483	3502	3522	3541	3560	3579	3598
23	3617	3636	3655	3674	3692	3711	3729	3747	3766	3784
24	3802	3820	3838	3856	3874	3892	3909	3927	3945	3962
25	3979	3997	4014	4031	4048	4065	4082	4099	4116	4133
26	4150	4166	4183	4200	4216	4232	4249	4265	4281	4298
27	4314	4330	4346	4362	4378	4393	4409	4425	4440	4456
28	4472	4487	4502	4518	4533	4548	4564	4579	4594	4609
29	4624	4639	4654	4669	4683	4698	4713	4728	4742	4757
30	4771	4786	4800	4814	4829	4843	4857	4871	4886	4900
31	4914	4928	4942	4955	4969	4983	4997	5011	5024	5038
32	5051	5065	5079	5092	5105	5119	5132	5145	5159	5172
33	5185	5198	5211	5224	5237	5250	5263	5276	5289	5302
34	5315	5328	5340	5353	5366	5378	5391	5403	5416	5428
35	5441	5453	5465	5478	5490	5502	5514	5527	5539	5551
36	5563	5575	5587	5599	5611	5623	5635	5647	5658	5670
37	5682	5694	5705	5717	5729	5740	5752	5763	5775	5786
38	5798	5809	5821	5832	5843	5855	5866	5877	5888	5899
39	5911	5922	5933	5944	5955	5966	5977	5988	5999	6010
40	6021	6031	6042	6053	6064	6075	6085	6096	6107	6117
41	6128	6138	6149	6160	6170	6180	6191	6201	6212	6222
42	6232	6243	6253	6263	6274	6284	6294	6304	6314	6325
43	6335	6345	6355	6365	6375	6385	6395	6405	6415	6425
44	6435	6444	6454	6464	6474	6484	6493	6503	6513	6522
45	6532	6542	6551	6561	6571	6580	6590	6599	6609	6618
46	6628	6637	6646	6656	6665	6675	6684	6693	6702	6712
47	6721	6730	6739	6749	6758	6767	6776	6785	6794	6803
48	6812	6821	6830	6839	6848	6857	6866	6875	6884	6893
49	6902	6911	6920	6928	6937	6946	6955	6964	6972	6981

The Napierian logarithm equals 2.3026 times the common logarithm.

$$\log_e n = 2.3026 \times \log_{10} n$$

TABLE 6.—MANTISSAS OF COMMON LOGARITHMS.—(Continued)

	0	1	2	3	4	5	6	7	8	9
50	6990	6998	7007	7016	7024	7033	7042	7050	7059	7067
51	7076	7084	7093	7101	7110	7118	7126	7135	7143	7152
52	7160	7168	7177	7185	7193	7202	7210	7218	7226	7235
53	7243	7251	7259	7267	7275	7284	7292	7300	7308	7316
54	7324	7332	7340	7348	7356	7364	7372	7380	7388	7396
55	7404	7412	7419	7427	7435	7443	7451	7459	7466	7474
56	7482	7490	7497	7505	7513	7520	7528	7536	7543	7551
57	7559	7566	7574	7582	7589	7597	7604	7612	7619	7627
58	7634	7642	7649	7657	7664	7672	7679	7686	7694	7701
59	7709	7716	7723	7731	7738	7745	7752	7760	7767	7774
60	7782	7789	7796	7803	7810	7818	7825	7832	7839	7846
61	7853	7860	7868	7875	7882	7889	7896	7903	7910	7917
62	7924	7931	7938	7945	7952	7959	7966	7973	7980	7987
63	7993	8000	8007	8014	8021	8028	8035	8041	8048	8055
64	8062	8069	8075	8082	8089	8096	8102	8109	8116	8122
65	8129	8136	8142	8149	8156	8162	8169	8176	8182	8189
66	8195	8202	8209	8215	8222	8228	8235	8241	8248	8254
67	8261	8267	8274	8280	8287	8293	8299	8306	8312	8319
68	8325	8331	8338	8344	8351	8357	8363	8370	8376	8382
69	8388	8395	8401	8407	8414	8420	8426	8432	8439	8445
70	8451	8457	8463	8470	8476	8482	8488	8494	8500	8506
71	8513	8519	8525	8531	8537	8543	8549	8555	8561	8567
72	8573	8579	8585	8591	8597	8603	8609	8615	8621	8627
73	8633	8639	8645	8651	8657	8663	8669	8675	8681	8686
74	8692	8698	8704	8710	8716	8722	8727	8733	8739	8745
75	8751	8756	8762	8768	8774	8779	8785	8791	8797	8802
76	8808	8814	8820	8825	8831	8837	8842	8848	8854	8859
77	8865	8871	8876	8882	8887	8893	8899	8904	8910	8915
78	8921	8927	8932	8938	8943	8949	8954	8960	8965	8971
79	8976	8982	8987	8993	8998	9004	9009	9015	9020	9025
80	9031	9036	9042	9047	9053	9058	9063	9069	9074	9079
81	9085	9090	9096	9101	9106	9112	9117	9122	9128	9133
82	9138	9143	9149	9154	9159	9165	9170	9175	9180	9186
83	9191	9196	9201	9206	9212	9217	9222	9227	9232	9238
84	9243	9248	9253	9258	9263	9269	9274	9279	9284	9289
85	9294	9299	9304	9309	9315	9320	9325	9330	9335	9340
86	9345	9350	9355	9360	9365	9370	9375	9380	9385	9390
87	9395	9400	9405	9410	9415	9420	9425	9430	9435	9440
88	9445	9450	9455	9460	9465	9469	9474	9479	9484	9489
89	9494	9499	9504	9509	9513	9518	9523	9528	9533	9538
90	9542	9547	9552	9557	9562	9566	9571	9576	9581	9586
91	9590	9595	9600	9605	9609	9614	9619	9624	9628	9633
92	9638	9643	9647	9652	9657	9661	9666	9671	9675	9680
93	9685	9689	9694	9699	9703	9708	9713	9717	9722	9727
94	9731	9736	9741	9745	9750	9754	9759	9763	9768	9773
95	9777	9782	9786	9791	9795	9800	9805	9809	9814	9818
96	9823	9827	9832	9836	9841	9845	9850	9854	9859	9863
97	9868	9872	9877	9881	9886	9890	9894	9899	9903	9908
98	9912	9917	9921	9925	9930	9934	9939	9943	9948	9952
99	9956	9961	9965	9969	9974	9978	9983	9987	9991	9996

The Napierian logarithm equals 2.3026 times the common logarithm.

$$\log_e n = 2.3026 \times \log_{10} n$$

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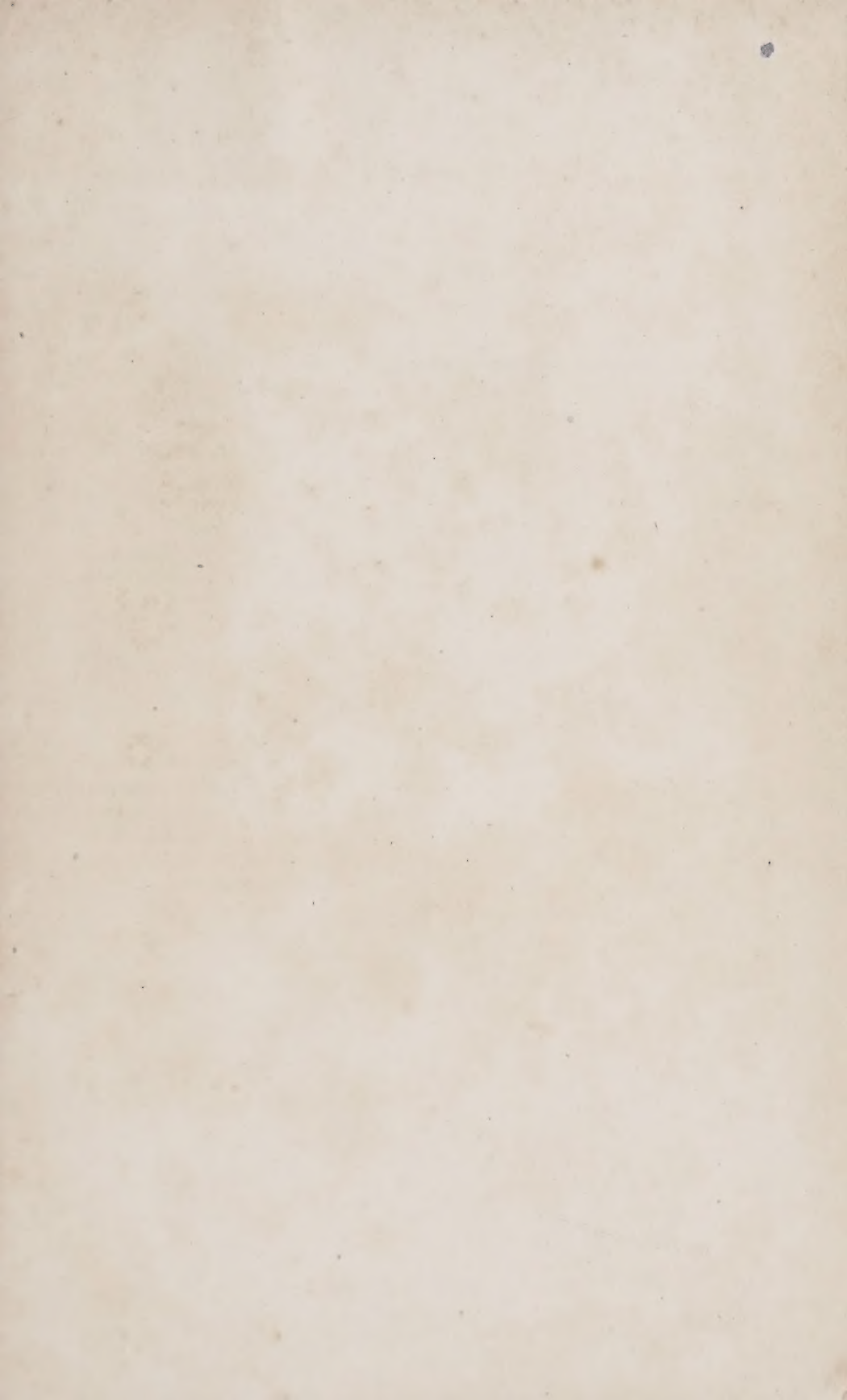
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